APPENDIX C: TECHNICAL REFERENCES (PAGES 341 THROUGH 392)
IS AVAILABLE IN ELECTRONIC FORMAT AT

HTTP://PARKPLANNING.NPS.GOV/PROJECTHOME.CFM?PROJECTID=33151

APPENDIX C: TECHNICAL REFERENCES

(AVAILABLE ONLINE ONLY)

APPENDIX C1: WAVE CLIMATE AND LONGSHORE SEDIMENT TRANSPORT ANALYSIS

SITE

The Indiana Dunes National Lakeshore (INDL) is located at the southern end of Lake Michigan, with the coastal boundaries of the park defined by Michigan City Harbor in the northeast and Gary/USX Steel Harbor in the west. Refer to figure 1 for a location map. This is a highly modified coastal environment. It is also a landscape of contrast, featuring some of the most unique beaches and coastal dune habitat in North America, located in between large lakefill projects, ports and harbors.

This report describes our technical analysis performed for the lake levels and waves at the site, along with longshore sediment transport modeling. Based on this technical analysis, it also describes the implications for the shoreline change rates documented in a companion report (1951/1952 to 2010 Shoreline Change Analysis, Indiana Dunes National Lakeshore, Baird 2011). Collectively, this information was utilized to develop long-term potential Shoreline Restoration Plans for the INDL.

WATER LEVEL AND WAVE ANALYSIS

This section of the report describes the procedures undertaken in order to quantify the lake level conditions and wave climate at the project site. Together, the waves and water levels determine the design conditions used to establish the level of shore protection required. For example, the established conditions will be used to design "soft" erosion mitigation techniques, such as beach nourishment and "hard" structures, such as breakwaters or groins (emergent or submerged).

Typically, various conditions are analyzed to determine the wave climate at a site in the Great Lakes. The USACE utilizes a set of design conditions established using the (10:20 and (20:10) criteria. The (10:20) and (20:10) method is a combined return period criteria that uses both the 1:10 year water level with the 1:20 year wave height, and the 1:20 year water level with the 1:10 year wave height, respectively. Whichever combination results in a larger design wave at the structure governs as the design condition.

Coastal erosion protection structures around the Great Lakes typically use 25 to 50-year design life engineering calculations. It is important to recognize that this assumption is no guarantee that the coastal structure will actually last for 25 or 50 years. A storm event that exceeds the design conditions may occur in any given year.

FIGURE 1: LOCATION MAP FOR THE INDIANA DUNES NATIONAL LAKESHORE

It is also noted that with a regular monitoring program in place and maintenance repairs as needed, the coastal structures might be functional at the end of their 25 to 50-year design life. For the purposes of this conceptual design study, a 50-year design life was assumed for engineering structures.

The following section describes a risk assessment approach to establish an appropriate set of design conditions for the site.

Risk Assessment to Establish Design Conditions

Risk is defined as the probability that a given design event (e.g., a specified combination of monthly mean water level, storm surge and wave height) will be reached or exceeded at least once during the project life. If the design event is reached or exceeded, there will be certain consequences that must be taken into consideration. For example, there may be damage to the structure and the possibility of habitat loss and economic damages.

The level of acceptable risk should be defined and accepted by the project Owner during the first stages of a project with a firm understanding of the implications for different levels of risk. The International Navigation Association (PIANC 2003) provides basic guidance on the selection of appropriate risk levels for breakwater design; this approach has also been adopted by the International Organization for Standardization (ISO) in the Draft International Standard 21650. PIANC establishes four safety classes (very low, low, normal, and high), and evaluates them based upon potential risk of human injury, environmental and economic consequences. This information provides some insight on the level of acceptable risk for design purposes. table 1 summarizes maximum acceptable risk based on various "safety class" levels (PIANC 2003), along with examples provided in ISO/DIN 21650.

The safety class and desired limit state selected for this project were based on our review of the PIANC guidance and will require additional consultation with the National Park Service (NPS) in a final design phase. At this time, the appropriate safety class for potential shoreline protection structures is assumed to be "very

TABLE 1: MAXIMUM ACCEPTABLE RISK

Safety Class	Indicators	SLS*	ULS**	Examples (ISO/DIS 21650:2007)
Very Low	No risk to human injury Small environmental consequences Small economic consequences	40%	20%	Small coastal structures.
Low	No risk to human injury Some environmental consequences Some economic consequences	20%	10%	Larger coastal structures such as breakwaters in deep water and exposed seawalls protecting infrastructure.
Normal	Risk to human injury Significant environmental consequences High economic or political consequences	10%	5%	Breakwaters protecting a LNG-terminal or power station.
High	Risk to human injury Significant environmental consequences Very high economic or political consequences	5%	1%	Sea dyke protecting a populated low land.

Source: PIANC, 2003.

Notes:

*Serviceability Limit State (SLS): e.g., overtopping, settlement of foundation soil

**Ultimate Limit State (ULS): e.g., foundation failure, failure of significant portion of structure low", and this relates to a condition where there is no direct risk of human injury and small environmental or economic consequences associated with the failure of the structure (i.e. impacts before it can be repaired). According to Serviceability Limit State (SLS), the acceptable maximum probability of failure during the lifetime of a structure of this description is 40% (PIANC 2003). These assumptions will have to be further discussed and verified with the NPS in a final design project phase.

Assuming a design life of 50-years and applying the standard formula (refer Equation 1) for calculating the risk of an event occurring, it was determined that the corresponding design return period event is 100 years.

EQUATION 1: RISK OF AN EVENT OCCURRING WITHIN A SPECIFIED DESIGN LIFE

$$Risk = 1 - \left(1 - \frac{1}{Tr}\right)^{DesignLife}$$

Lake Level and Storm Surge Analysis

Water levels on Lake Michigan vary both in the long-term in response to continental scale climatic conditions, as well as in the short term due to the passage of individual storm events, creating short duration storm surges. Storm surge is a local increase in the water level caused by wind stresses applied to the water surface and regional scale pressure gradients.

The computer model HYDSTAT was used to complete a joint probability analysis (JPA) for long term monthly mean lake levels and short term surge data. HYDSTAT is a well recognized model that has been used extensively around the Great Lakes for flood level and water related hazard studies (USACE 1988; OMNR 1989). Refer to Baird (2010) for additional information on the model and recent applications throughout the Great Lakes Basin.

To assess storm surge, 41 years of hourly measured water level data from the National Oceanic & Atmospheric Administration (NOAA) Calumet Harbor gage (9087044) on Lake Michigan were obtained for the period 1970-2010. A surge event was defined as any period of time where the lake level was greater than +0.8 ft above the still water level for more than 3 consecutive hours, with a minimum of 24 hours between successive events. From this population of events, the largest annual surge was selected for the 41 year period of record. These surge events were used for the first independent variable and extreme value analysis in HYDSTAT.

The lakewide monthly mean data for Lake Michigan was analyzed from 1954 to 2010 to establish an annual maximum monthly mean lake level. 1954 corresponded to the beginning of the temporal analysis in the 1988 USACE study. This annual maximum series of monthly mean lake levels was used as the second independent variable for the HYDSTAT analysis.

HYDSTAT was then used to perform a JPA on the two independent variables (still water level and storm surge) and select an appropriate probability distribution for the data. The Log Pearson 3 distribution was selected for the HYDSTAT output and used to establish the return period lake levels in table 2 on page 330. The lake levels are presented as an elevation relative to Vertical Datum IGLD85, and above Low Water Datum of 577.5 feet. For reference, table 2 also includes the extreme lake levels with a return period of 10, 50, 100 and 500, as published by the USACE 1988 study. It should be noted that this study relied on data from 1954 to 1986, which is a much shorter temporal duration than our present analysis (e.g., 24 years of additional information is now available). Since some of those years featured very high lake levels (e.g., 1998), the updated results in table 2 are approximately 0.7 ft higher than the levels reported in the 1988 USACE report.

The 1988 USACE report was updated in 1993 and the findings are summarized in a report entitled Design Water Level Determination on the Great Lakes (USACE, 1993). The reported 10-, 50-, and 100-Year lake level (still water with combined surge) values are 582.94, 583.41 and 584.34 feet IGLD85, respectively. Refer to table 2 for summarized information.

TABLE 2: RESULTS OF THE JOINT PROBABILITY ANALYSIS (SURGE AND MEAN LAKE LEVEL) FOR THE CALUMET GAGE

Return Period (years)	Lake Level (ft LWD)	Baird Lake Level (ft IGLD 85)	USACE 1988 (ft IGLD 85)	USACE 1993 (ft IGLD 85)
2	4.0	581.5	–	–
5	5.1	582.6	–	–
10	5.7	583.2	582.5	582.9
25	6.4	583.9	–	–
50	6.8	584.3	583.6	583.4
100	7.2	584.7	584.0	584.3
200	7.5	585.0	–	–
500	7.9	585.4	584.9	–

Notes:

ft = foot (feet)

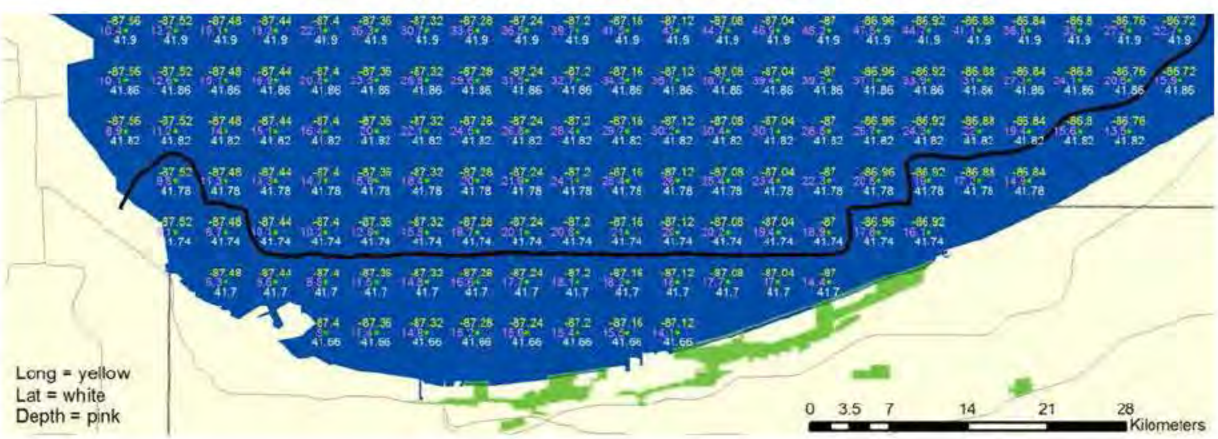
USACE = U.S. Army Corps of Engineers

Wind-Wave Hindcast with the WAVAD Model

Wave data for the site was obtained from Baird's in-house Lake Michigan wave hindcast model at a point in the central portion of the study area (Lat 41.66, Long -87.12). Refer to figure 2, which identifies all the model output locations (modeling results considered) for the southern portion of Lake Michigan. The water depth at the selected point is 46 ft below CD. This data was transformed to a depth of 6 ft below CD, which is the anticipated depth for any potential engineering structures that might be considered. For reference, the nature of these potential structures had not been determined at the time the hindcast analysis was performed; therefore, it was assumed the structures could include submerged shoals (underwater stone berms) that enhance local beach conditions.

WAVAD was developed by the Engineering Research Development Center, Coastal Hydraulics Laboratory of the USACE (Resio and Perrie, 1989). The model simulates wave growth and propagation in deep water. For additional information on the WAVAD modeling and similar applications in the Great Lakes Basin, refer to the Baird summary presented after the references list.

FIGURE 2: WAVAD GRID POINTS FOR SOUTHERN LAKE MICHIGAN



At a reference water depth of 6 ft below CD for engineering structures, it was determined the waves are depth limited at the site using the lake levels presented in table 2 on page 330. In other words, the wave height is controlled by water depth. Consequently, the return period for the design event is directly related to the extreme water levels shown in table 3.

As outlined in the risk assessment, a 100 year event was recommended for designing engineering structures. This corresponds to a lake level of 7.2 ft above CD and a breaking wave height of 10.7 ft.

LONGSHORE SEDIMENT TRANSPORT MODELING

The results of the longshore sediment transport modeling completed for the study area are described in this section and build on the previous technical investigation completed by Baird (2004) at Michigan City.

Regional Sediment Modeling

The COSMOS 2-dimensional computer model was applied to calculate the Longshore Sediment Transport (LST) rates at 2 km (1.25 miles) intervals along the shoreline between New Buffalo and the Port of Indiana Industrial Complex over the 45-year period of 1956 to 2000. The beach profiles extended out to a depth of approximately 15 m (49 feet) below CD and were assumed to be covered with a sandy layer.

A uniform sand grain size of 0.3 mm was used based on sediment samples collected during a previous site visit (Baird 2003).

Waves in the study area were transformed to a 15 m water depth at each calculation point using linear refraction and shoaling equations. The input wave data had a yearly scatter format and was split into North and West wave files (separated based on a shore perpendicular azimuth at each profile) to estimate contributions from each direction. The contributions will be referred to as southward and northward components, respectively, hereafter. Calculations were conducted at almost 30 different points along the shoreline.

Figure 3 on page 332 shows the 45-year average annual cross-shore distribution of LST for a typical beach profile. Sediment motion extends out to beyond 10 m (33 feet) below CD. The existence of two bars on the profile results in two peaks in the LST curves. The shallow depths over the bar induces wave breaking and results in larger depth average currents and near-bottom orbital velocities, leading to higher LST rates. There is also a third peak near the shoreline in the swash zone followed by a change in net transport direction from south to north. The northward transport is the cumulative effect of smaller waves that arrive mostly from the west, which is the dominate wind direction but features a smaller fetch compared to the north. Regional variations of LST are discussed in the following subsections.

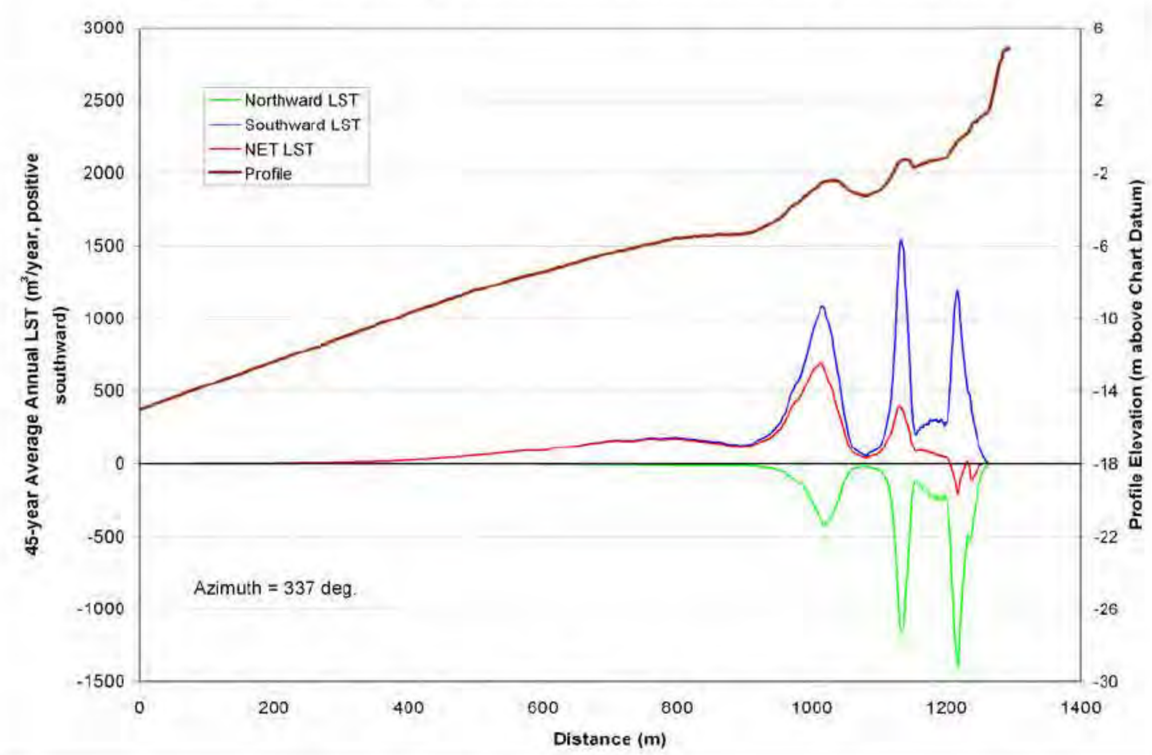
TABLE 3: RETURN PERIOD LAKE LEVELS AND WAVE HEIGHTS

Return Period (years)	Lake Level (ft LWD)	Total Water Depth (ft)	Depth Limited Wave Height (ft)
2	4.0	10.0	8.2
5	5.1	11.1	9.1
10	5.7	11.7	9.6
25	6.4	12.4	10.1
50	6.8	12.8	10.4
100	7.2	13.2	10.7

Notes:

ft = foot (feet)

FIGURE 3: CROSS-SHORE DISTRIBUTION OF LST FOR A TYPICAL BEACH PROFILE



LST for Pre-Harbor Shoreline

In order to understand the regional LST pattern prior to construction of the harbors and ports, COSMOS runs were completed for the shoreline and the shoreline orientation based on the 15 m contour taken from the 1874 historical survey. Calculated pre-harbor regional LST and its northward and southward components are shown in figure 4 on page 333. In this figure, distances are referenced to Michigan City Harbor which is located at 0 km. It may be seen that net LST decreases gradually from 250,000 m^3/year (327,000 yd^3/year) at New Buffalo to about

170,000 m^3/year (222,000 m^3/year) at the Port of Indiana Industrial Complex. These results suggest historically the shorelines between New Buffalo and the Industrial Complex were accreting. This long term trend of accretion also supports the lake level studies of Baedke and Thompson (2000), which document the formation of the Indiana Dunes at the southern end of Lake Michigan over the last 4,700 years.

LST Estimates for Existing Conditions

Calculated regional LST rates for the existing conditions between New Buffalo and the Port of Indiana Industrial Complex are shown in figure 5 on page 333. The calculated historic rates from the previous section are also shown in this figure for comparison. While the potential incoming and outgoing transport rates to the study area are the same as their historic rates, differences are noticed around the Michigan City Harbor. It may be seen that the formation of the updrift fillet and the resulting change in the shoreline orientation has resulted in a stronger negative LST gradient than the pre-harbor condition. This fact combined with the trapping potential of the harbor are the principal factors responsible for the creation and growth of the fillet beach. Immediately downdrift of Michigan City Harbor, a positive or increasing LST gradient extending to about 4 km downdrift is calculated. This positive LST gradient and the sediment budget deficit at Mount Baldy (Baird 2004) are responsible for the observed erosion in this area.

FIGURE 4: LST FOR PRE-SETTLEMENT SHORELINE ORIENTATION

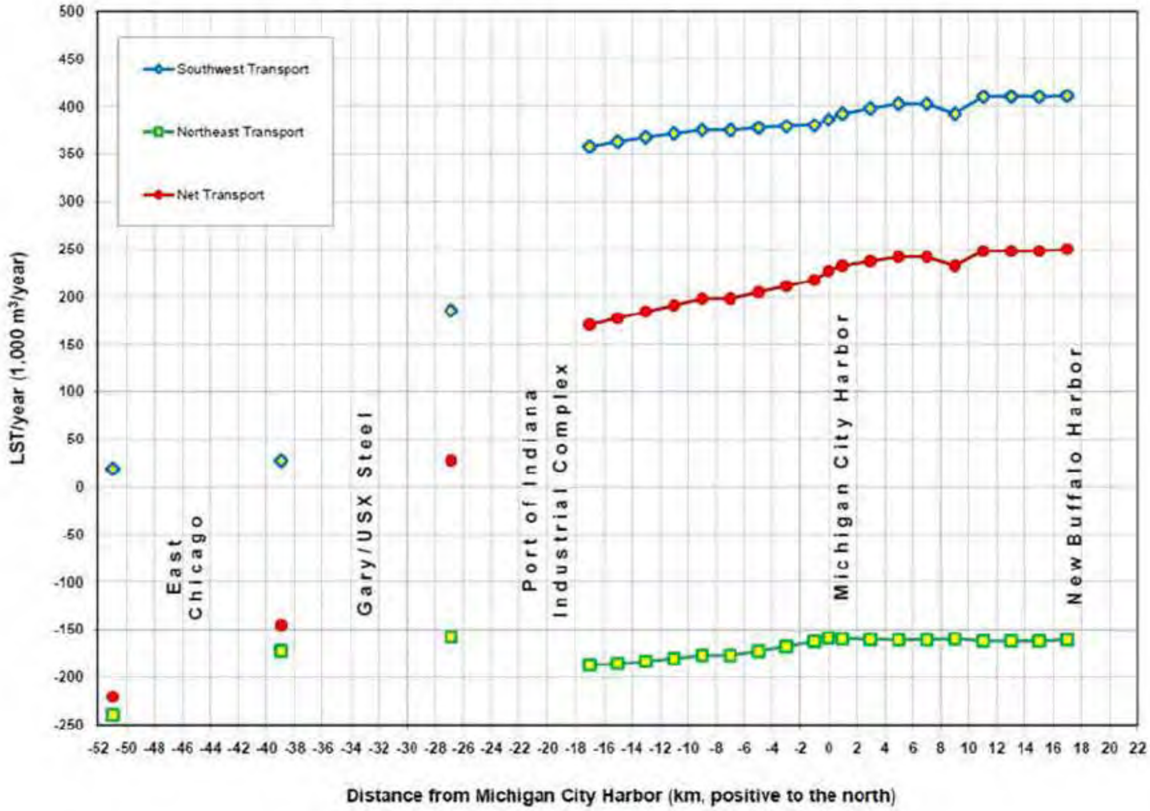
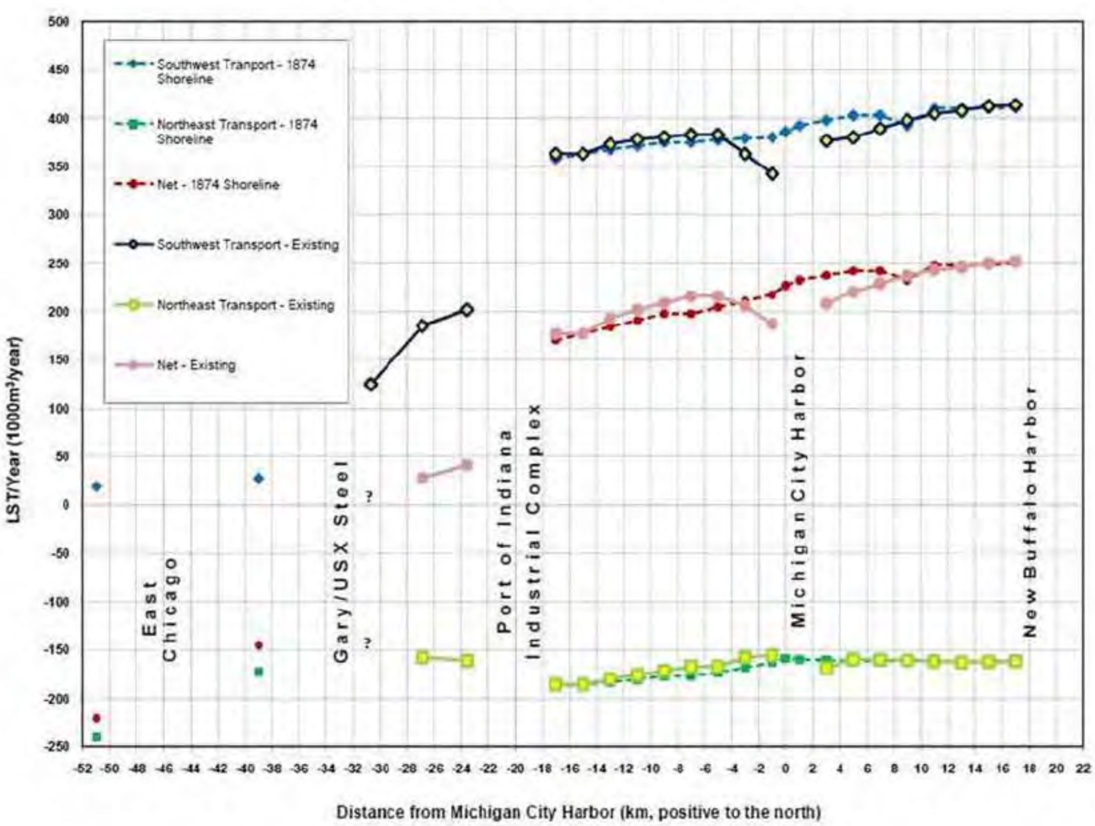


FIGURE 5: LST FOR CURRENT SHORELINE ORIENTATION



IMPLICATIONS FOR FUTURE SHORELINE CHANGE RATES

The following sections discuss the implications of the sediment transport modeling for future shoreline change rates in the study area, and provide baseline conditions for development of project restoration plans.

Future Trends at Harbors

There are three main areas within the project shoreline that constitute littoral barriers, disrupting the natural sediment flow in an alongshore direction. These man-made harbors trap sediment on the northeast or updrift side and lead to erosion on the southwest or downdrift side.

The three main harbors are:

- Michigan City Harbor (initial construction in 1834, Harbor completed in early 1900s)
- Port of Indiana Industrial Complex (constructed in the late 1960s)
- Gary USX Steel (constructed in early 1900s)

The total impacts of these harbors are somewhat difficult to quantify. The analysis to estimate the total sediment volumes is based on detailed aerial photographs from pre-Harbor conditions to present; quantities dredged, and harbor bypassing. Based on preliminary calculations, the total quantities of accreted sediment immediately north-east of the harbors is:

- Michigan City Harbor: 28.2M cubic meters (36.8M cubic yards). Does not include the volume of sediment dredged in the navigation channel and artificially bypassed;
- Port of Indiana Industrial Complex: 3.5M cubic meters (4.6M cubic yards). Does not include sediment dredged and artificially bypassed/backpassed, which totals 1.7M cubic meters (2.2M cubic yards); and
- Gary USX Steel: 2.2M cubic meters (2.9M cubic yards). This is based on the current shoreline orientation defined by the confined disposal facility constructed post-1950.

Figures 6, 7, and 8 on pages 335 and 336 document the fillet beaches and historical shoreline change rates at the three harbors.

Trends for the National Lakeshore

A companion report entitled 1951/52 to 2010 Shoreline Change Analysis, Indiana Dunes National Lakeshore (Baird 2011) documented trends in the study area shoreline over the last 60 years. The following bullet points comment on anticipated future trends based on the findings of this report and the status quo for sediment bypassing and beach nourishment activities within the study area (refer to figure 6 in the Baird (2011) report for the locations of Reaches A to G):

- **Reach A - Mount Baldy Erosion Zone**: Despite the placement of over 1 million cubic yards of beach nourishment since 1974, the beach and dunes immediate downdrift of the Michigan City Harbor continued to erode. Based on the LST modeling and the downdrift sediment budget deficit, this trend will continue for the status quo beach nourishment program (approximately 29,000 cubic yards per year, long-term average quantity);
- **Reach B – Beverly Shores to the Middle of Dune Acres**: The long term trend of “dynamically stable” is anticipated to continue. Beach position will be dynamic and respond to changes in lake levels. Locally, periods of erosion may threaten infrastructures, such as the revetment protecting portions of Lake Front Drive along Beverly Shores;
- **Reach C (Port of Indiana Industrial Complex Fillet Beach) and Reach E (Town of Ogden Dunes)**: The shoreline position in these two reaches is highly modified by the Port of Indiana Industrial Complex, dredging and mechanical sediment bypassing. The shoreline trend for Reaches C and E will be highly dependent on the degree of sediment management in the future, which may be investigated by as part of a reconnaissance study by the USACE (anticipated 2012). The current trends are anticipated in the future;

- **Reach F – West Beach to Miller**: The trend of dynamically stable will continue in the future if the status quo for sediment bypassing continues; and
- Reach G – Gary USX Steel Harbor Fillet Beach: Continued fillet beach growth is anticipated.

FIGURE 6: 1834 TO 2002 SHORELINE COMPARISON AT MICHIGAN CITY

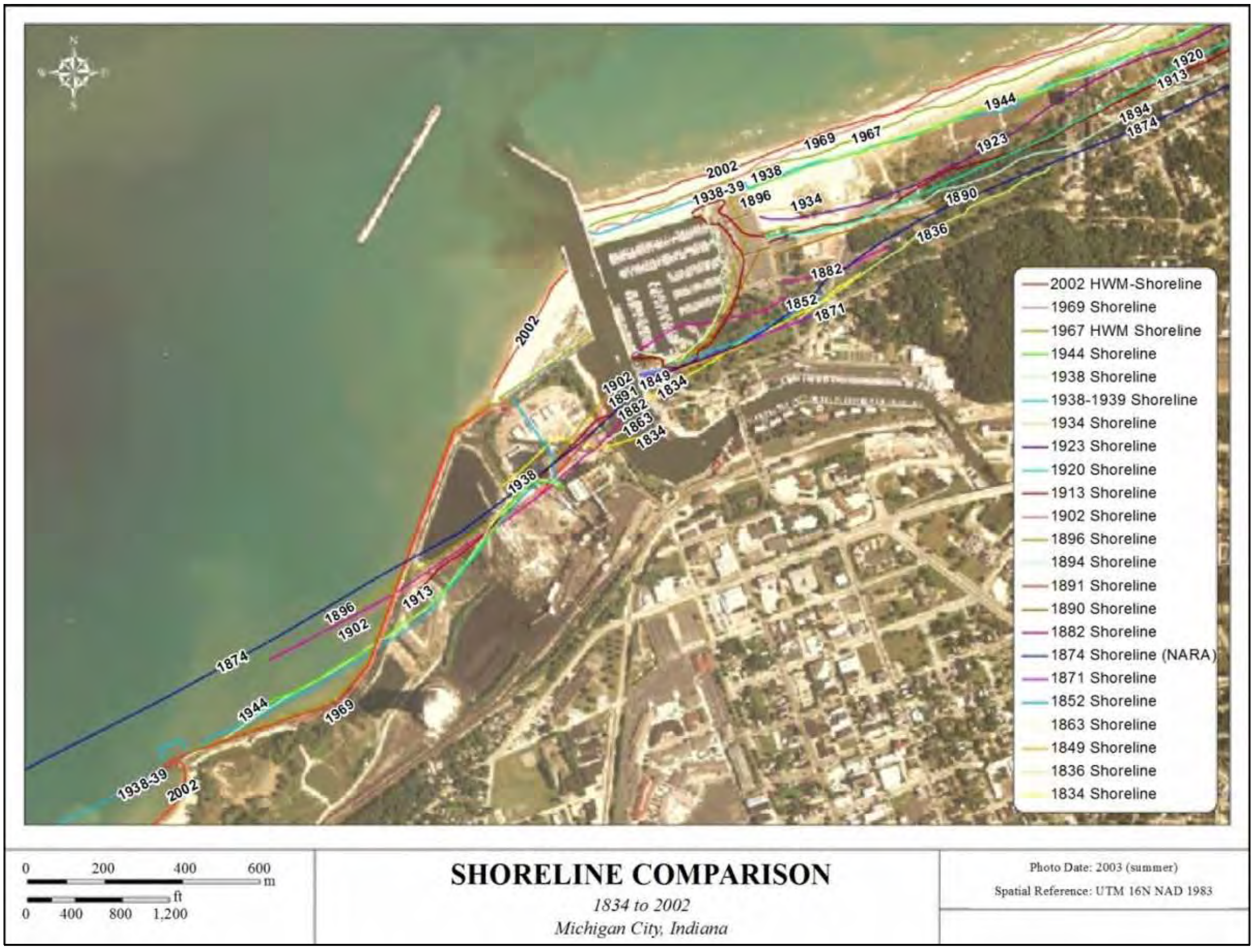


FIGURE 7: 1951/1952 TO 2010 FILLET BEACH AT THE PORT OF INDIANA INDUSTRIAL COMPLEX

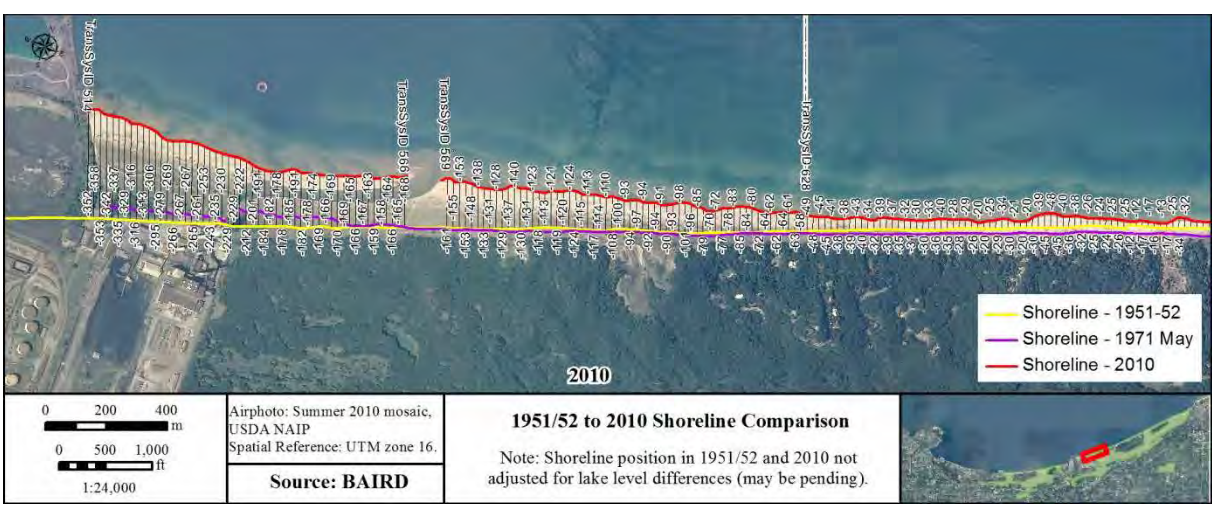
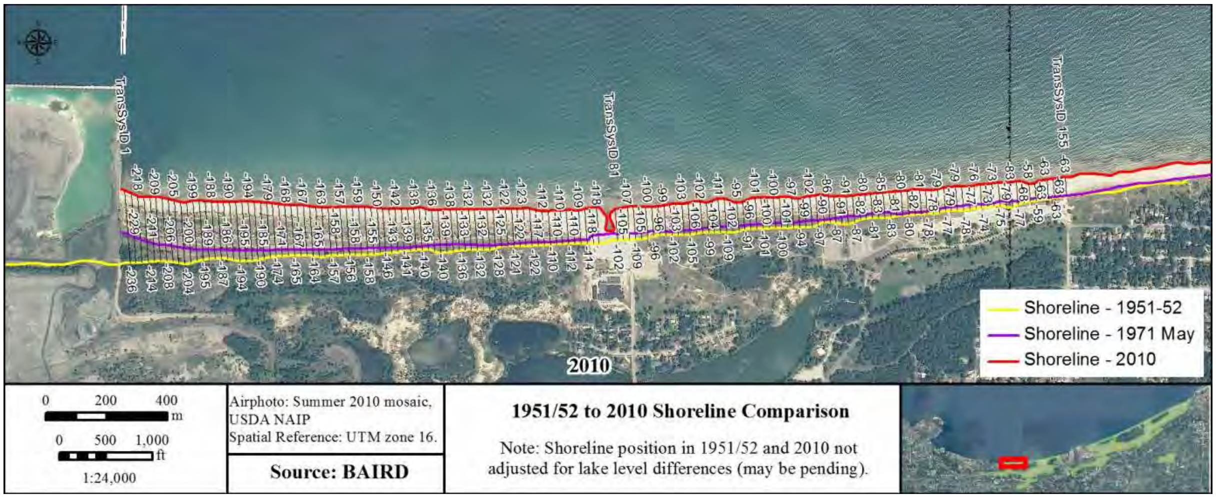


FIGURE 8: 1951/1952 TO 2010 FILLET BEACH AT THE GARY/USX STEEL HARBOR



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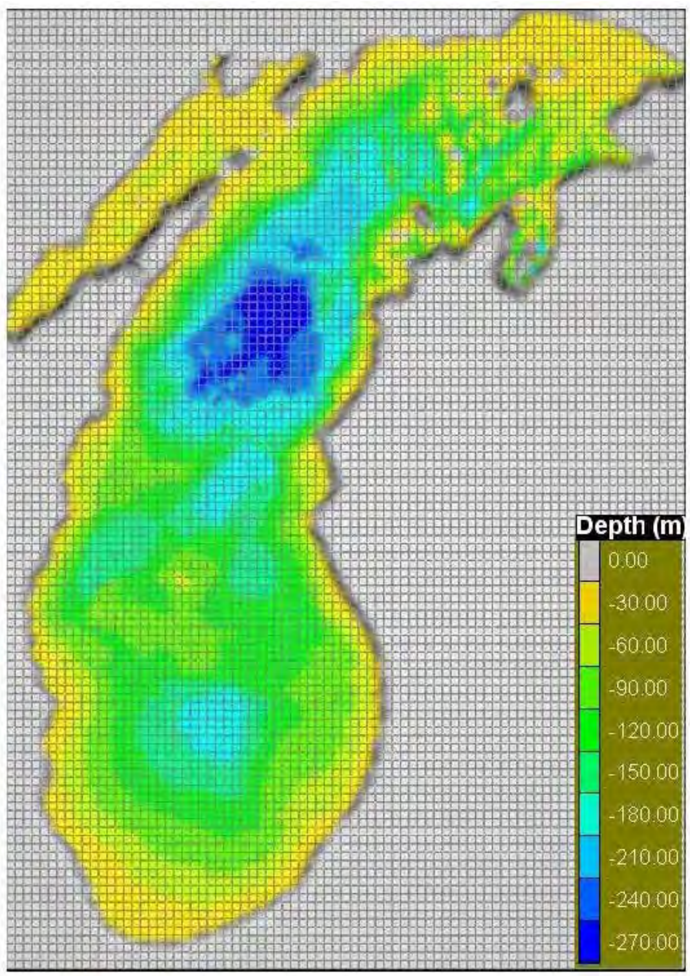
APPENDIX C2: LAKE MICHIGAN WAVAD HINDCAST — 1982 TO 2007

The wave climate for the southern end of Lake Michigan was initially evaluated with the aid of WIS data (specifically LM007) but it did not cover a suitable temporal period (WIS extends from 1956-1987) and was only 3 hour data. Therefore, a limited WAVAD wind-wave hindcast was completed for Lake Michigan (1982-2007), with output saved for the grid cells for the southern end of the lake. The primary input to WAVAD was 25 years of wind data obtained from offshore NOAA buoy #45007.

Since the buoy is decommissioned in the winter, this period was covered using wind data from Milwaukee Mitchel Airport. Figure 1 shows the model grid, which contains 82 x 116 grid points. The grid spacing is 0.04 deg.

A detailed description of the WAVAD model and application on Lake Ontario is provided in Baird (2003) and Scott et al.(2004). A description of a recent application on Lake Erie is provided in Baird (2008).

FIGURE 1: WAVE MODEL GRID



The model results were verified against the offshore buoy data. Figure 2 presents the quantile-quantile (Q-Q) plot between measured and modeled output at the offshore buoy location. Figure 3 on page 339 shows the time series comparison of measured and modeled data. In general, the modeled wave height results agree well with measured data, but slightly underestimates the large waves (Hm0 >2.5 m). Figure 4 on page 340 presents a snapshot of the model result.

FIGURE 2: Q-Q COMPARISON BETWEEN MEASURED AND MODELED WAVE HEIGHT

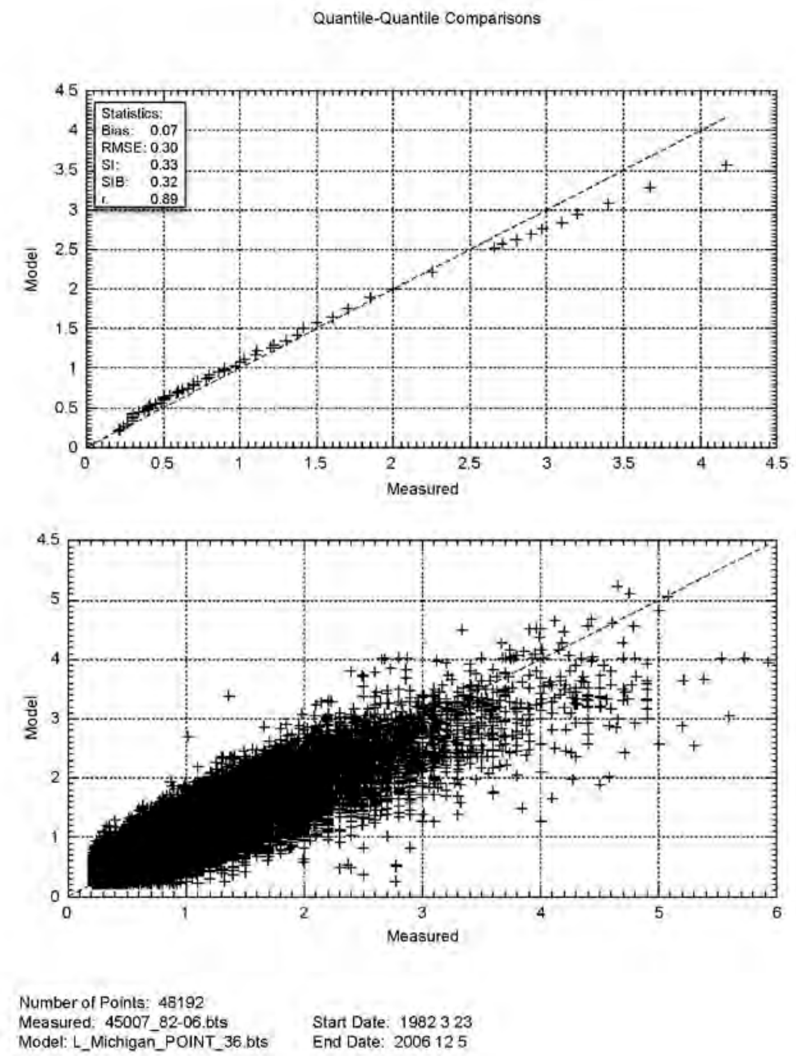


FIGURE 3: TIME SERIES COMPARISON BETWEEN MEASURED AND MODELED RESULT

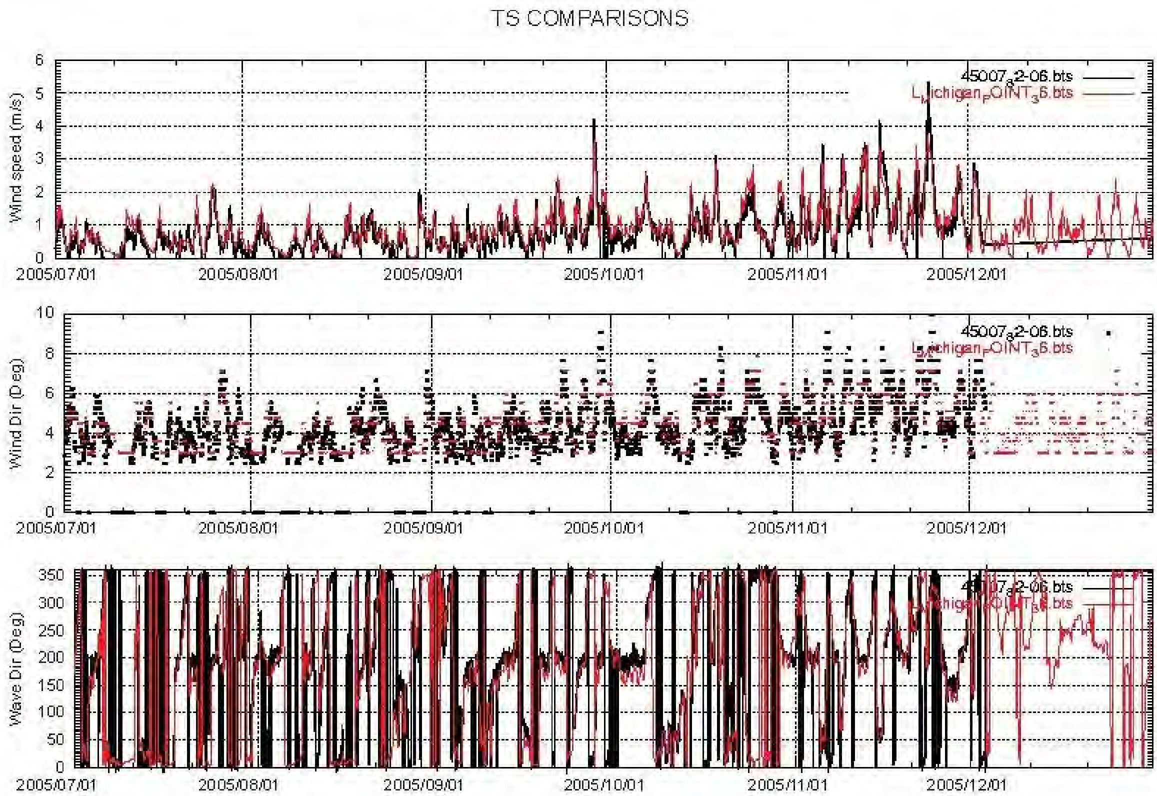
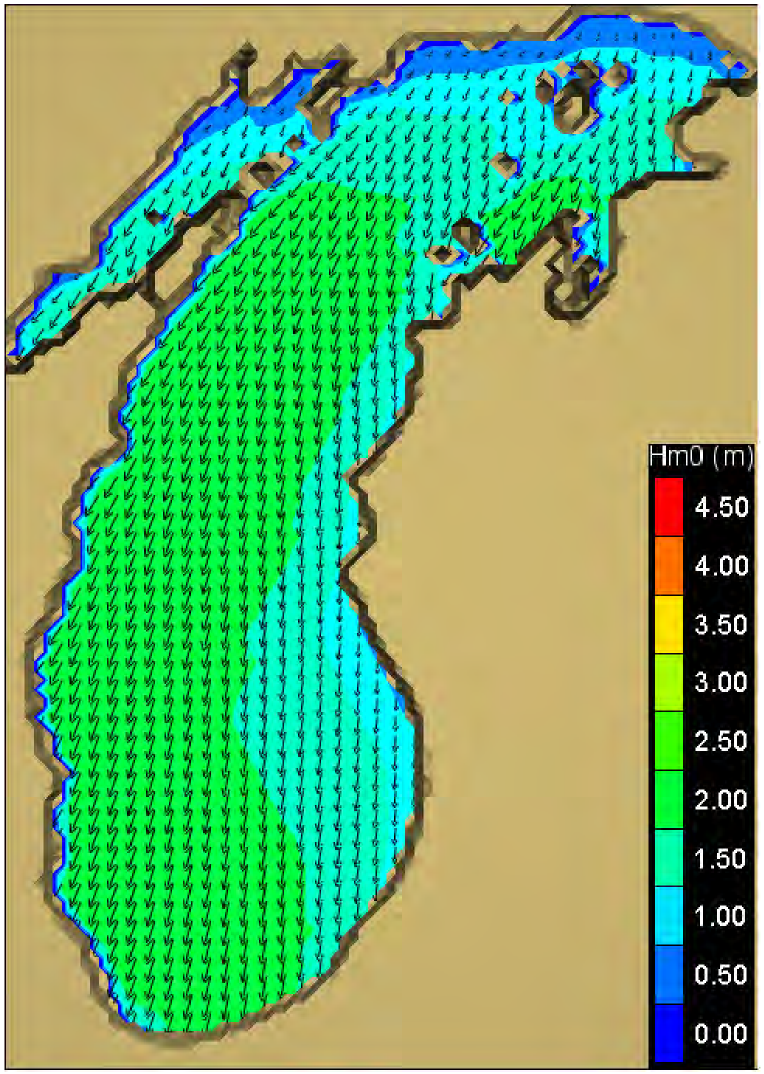


FIGURE 4: A SNAPSHOT OF WAVE MODEL RESULT



APPENDIX C3: 1951/1952 TO 2010 SHORELINE CHANGE ANALYSIS

SITE

Indiana Dunes National Lakeshore (INDL) is located at the southern end of Lake Michigan, with the coastal boundaries of the park defined by Michigan City Harbor in the northeast and Gary/USX Steel Harbor in the west. Refer to figure 1 for a location map. This is a highly modified coastal environment. It is also a landscape of contrast, featuring some of the most unique beaches and coastal dune habitat in North America, located in between large lakefill projects, ports and harbors.

This report describes the methods, results and implications of a shoreline change analysis for Indiana Dunes National Lakeshore completed with aerial photography from 1951/52 to 2010. The analysis is regional in nature, not focused on individual properties or a small segment of beach. Rather, this is a high level analysis of long term changes in the shoreline position over the last 60 years.

Older aerial photographs than 1951 might exist to document the shoreline evolution and the construction of man-made structures (the first jetties at Michigan City were constructed in 1836). However, the shoreline chance focus is on understanding the last 60 years of data and using this information to make management decisions for future project planning and implementation.

Another set of acquired aerial photographs covered the period of May 1971, which closely follows the completion of the lakefill project for the Port of Indiana.

INFLUENCE OF LAKE LEVELS AND STORMS

This region of Lake Michigan is classified as a sandy shoreline and in fact is one of the sandiest regions of the entire Great Lakes (Baird 2001). In other words, there is an abundance of sand on the lake bottom, along the beaches and in the dunes. In a completely natural system, which this is not, sand is transported in both a longshore and cross-shore direction in response to waves and currents generated during storms. Over long temporal periods, the magnitude and directionality of the storms influences the rate at which sand is transported along the coast and ultimately the resulting morphology of the shoreline. From previous technical studies, the net direction for longshore sediment transport within the limits of the study are from the northeast to the southwest (Baird 2004). Additional sediment transport modeling was completed to quantify the longshore rates (see Wave Climate and Longshore Sediment Transport Analysis).

FIGURE 1: LOCATION MAP FOR INDIANA DUNES NATIONAL LAKESHORE

Sandy shorelines are, by definition, dynamic. The position of the waterline, beach width and dunes are constantly responding to changes in lake levels and severe storm events. For example, the nearshore lake bottom, bars and beach respond to periods of rising lake levels by transferring sediment offshore (in a cross-shore direction), often leading to erosion of the dune and beach. Conversely, during periods of falling or low lake levels, sand is transferred onshore, beach width increases and aeolian processes transfer more sand into the foredune. This is typically a period of beach and dune building in the Great Lakes.

The long term lake level cycles for Lake Michigan, as recorded by the lakewide monthly mean water level, are presented in figure 2. Low Water Datum (LWD) is noted with the red line. The natural range for the still water level is almost 7 feet, which excludes the effects of storm surge. Since 1998, Lake Michigan water levels have been fluctuating in a range close to LWD, and for many locations within the study area, beaches have responded by migrating lakeward, new foredunes are growing and dune vegetation has migrated lakeward. Refer to the beach conditions in figures 3 and 4. Both pictures document a growing broad wide foredune; given the lack of shrub/woody vegetation, this accumulation began during the current low lake level period.

During periods of rising lake levels or the highs recorded in the early 1970s, mid 1980s or late 1990s, the beaches within the study area would have been significantly smaller as sand is transported in an offshore direction. In some locations, active dune erosion was likely occurring during severe storm events. In figures 3 and 4, the limit of vegetation was likely much closer to the deciduous tree line along the older dune crest.

In addition to the cross-shore response of the beaches to fluctuating lake levels, the change in the water surface elevation from the low to high cycles also exerts a strong influence on beach conditions by either exposing or covering a significant portion of the sandy beach.

FIGURE 2: LAKE MICHIGAN MONTHLY MEAN LAKE LEVELS, 1865 TO PRESENT

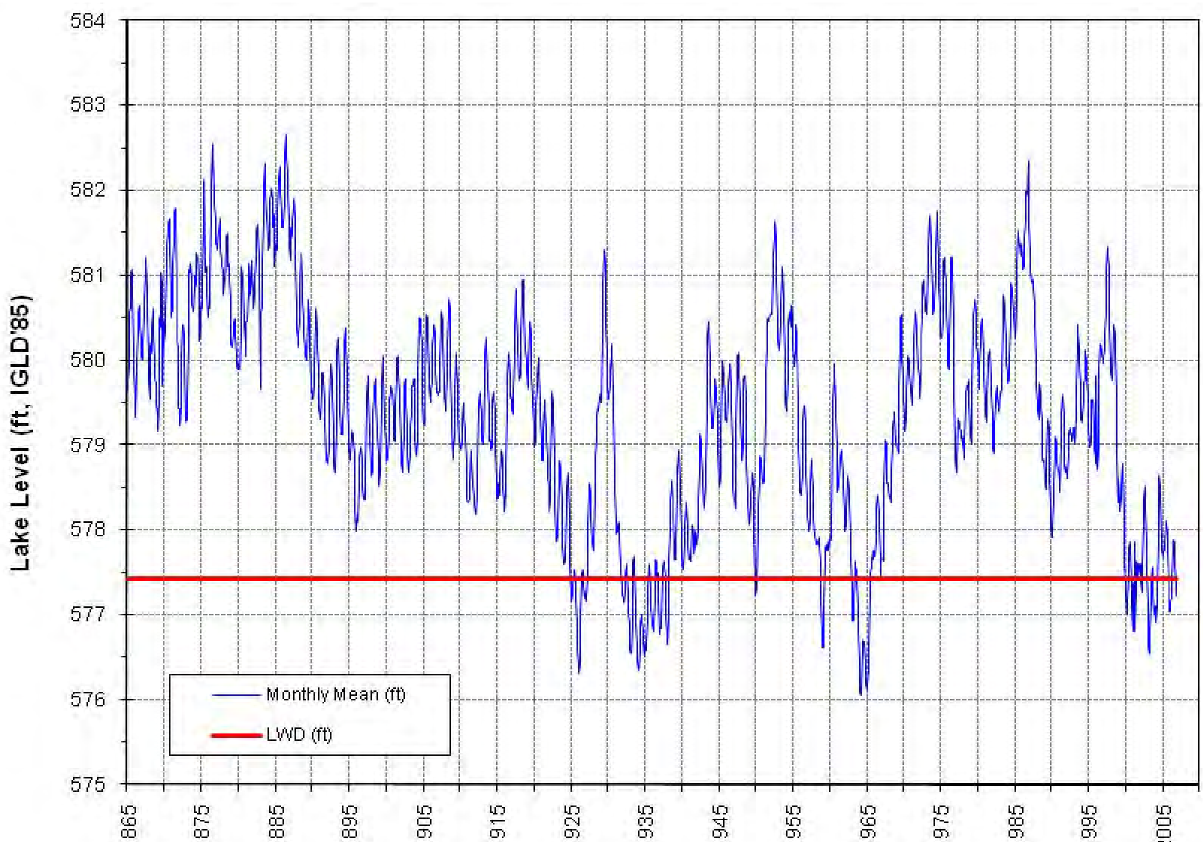
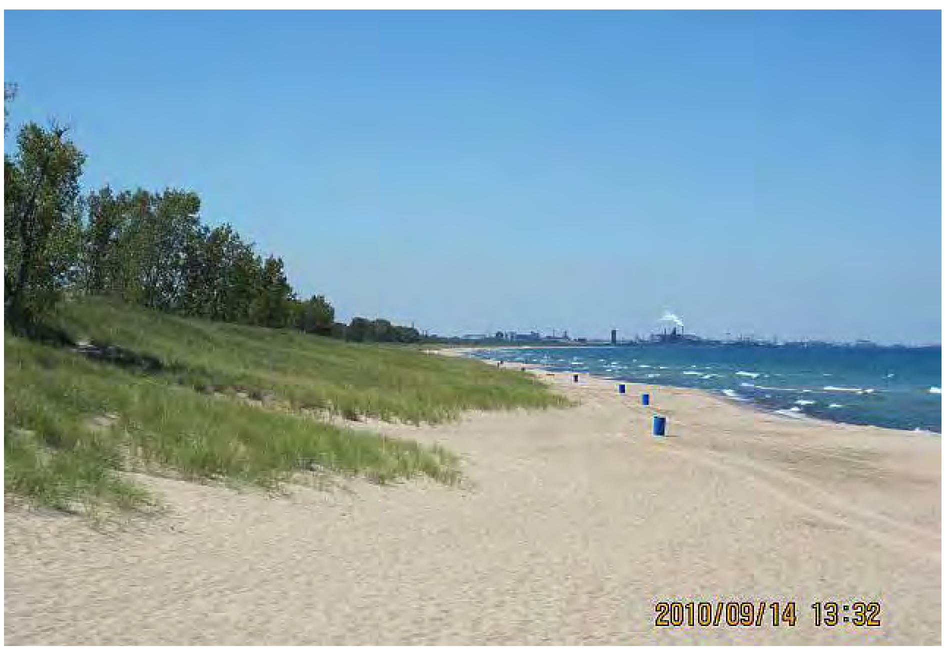


FIGURE 3: BEACH AT THE BOUNDARY OF BEVERLY SHORES AND INDIANA DUNES STATE PARK (LOOKING NORTHEAST)

FIGURE 4: BEACH CONDITIONS AT WEST BEACH, LOOKING WEST



INFLUENCE OF COASTAL STRUCTURES ON LONGSHORE SEDIMENT TRANSPORT

As discussed in Section 2.0, the direction of net longshore sediment transport within the study area is from the northeast to the southwest. When large coastal structures, such as a harbor or port, are constructed along the shoreline, they disrupt the natural flow of sediment. Typically, sediment accumulates on the updrift side of the structure, as it acts much like a large groyne. Refer to figure 5 for a conceptual sketch of this process. Downdrift of the structure, erosion typically occurs on the shadow of the port or harbor, as depicted in figure 5 for the groyne.

Within the limits of the study area, the shoreline evolution has been influenced by three very large port and harbor structures, namely the Michigan City Harbor, which is protected by Federal jetty structures, the Port of Indiana Industrial Complex, and the Gary Indiana/US Steel Harbor. The first structures at Michigan City were constructed in 1836 and have trapped approximately 36.6 million cubic yards of sediment (Baird 2005). The Port of Indiana Industrial Complex was much more recent, with construction completed in the late 1960s. The Gary Indiana/US Steel followed shortly after the Port of Indiana Industrial Complex. The influence of these large coastal structures on shoreline evolution within the study area is discussed in Section 5 of this report.

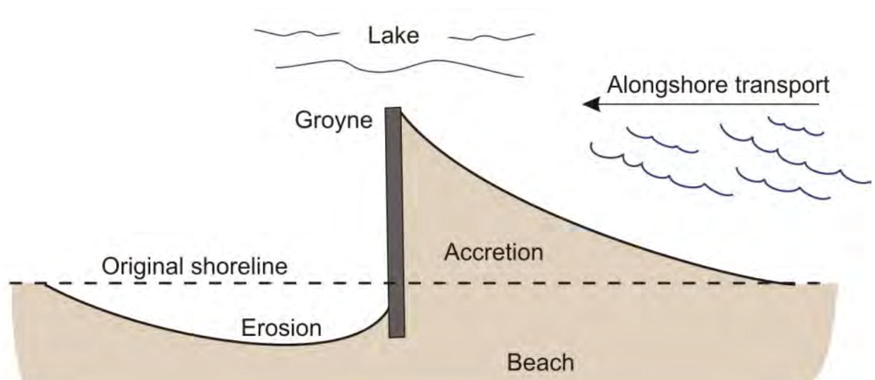
METHODS

The comparison of the shoreline position is based on aerial photo interpretation. Using photos from different temporal periods provides insight into long term trends. In order to compare photos from different temporal periods, the photos must be orthorectified. The orthorectification process takes aerial photos and removes the visual distortions created by topographical variations and the camera lens. Once an aerial photo has been orthorectified, it is commonly referred to as an orthophoto. When aerial photos from different time periods are orthorectified to a common geographic base, direct measurements and comparisons can be made between them.

The most recent set of aerial photographic imagery obtained for the study area is Summer 2010 from the US Department of Agriculture (USDA), Farm Service Agency (FSA), Aerial Photography Field Office (APFO), National Agriculture Imagery Program (NAIP).

These are provided by the USDA as ready-to-use orthophotos. The orthophotos have a 1 meter (3 feet) ground resolution. The oldest set of available and acquired aerial photos with sufficient resolution detail is a set of photos

FIGURE 5: INFLUENCE OF COASTAL STRUCTURES (GROYNES) ON BEACH ACCRETION AND EROSION



from December 1951 and March 1952 from the US Department of the Interior (USDI), US Geological Survey (USGS). These photos were orthorectified using PCI Geomatica's OrthoEngine software, using ground control information taken from the USDA 2010 orthophotos and using an elevation model provided by the USGS. These orthophotos have a ground resolution of 3 meters (9 feet).

To compare the shoreline position change between these two time periods, the visible water's edge was digitally traced using E.S.R.I.'s ArcGIS ArcMap software at a scale of 1:3,000 and is considered as shoreline for the water level on the day of the photography. Since the water level in 1951/52 and 2010 were not identical, direct measurements between these two shorelines would introduce a bias associated with the lower lake level conditions during the 2010 photography. Table 1 summarizes all the photographs utilized in this analysis, along with the date of capture and the associated monthly mean lake level (ft, IGLD'85).

TABLE 1: SUMMARY OF AIR PHOTOGRAPHS AND MONTHLY MEAN LAKE LEVELS

Date	Shoreline Extent	Monthly Mean Lake Level (feet)
12/9/1951	Gary to Beverly Shores	580.5
3/27/1952	Beverly Shores to Michigan City	580.6
5/3/1971	Gary to Port of Indiana Industrial Complex	580.3
5/14/1971	Port of Indiana Industrial Complex to Michigan City	580.3
06 to 08/2010	Entire Study Area	578.3

The lake surface elevation difference between the 1951/52 photos and those captured in 2010 was 2.25 ft. To correct for this difference in lake levels, the beach and nearshore slopes for the sections of shoreline between Michigan City and the Port of Indiana Industrial Complex were analyzed next. Using recent LIDAR topography and bathymetry, the average beach slope between the 580.5 to 583.5 ft contours (IGLD'85) was calculated to be 1:18 (V:H). The same procedure was applied to a 2,300-foot stretch of shoreline between the Port of Indiana Industrial Complex and Gary. Here the calculated beach slope was 1:15 (V:H).

Since the trend in lake levels between the 1951/52 aerial photograph and 2010 was a drop in water level of 2.25 ft, and the former lakebed in 1951/52 is now exposed due to lower water level conditions, the nearshore slope was also calculated between the 570 and 580 ft contours for the shoreline between Michigan City and the Port of Indiana Industrial Complex. Based on the detailed LIDAR bathymetry, an average nearshore slope of 1:35 (V:H) was calculated. This slope (1:35) was used to correct the shoreline change transects described in the following paragraphs.

To measure the change between these two shorelines, Baird has developed a tool that automates the process of measuring transects between the shorelines at a user defined interval (Zuzek et al, 2003) along a fixed baseline. For this study area, an interval of 66 feet was chosen, resulting in 1,450 transect lines measuring the difference in the shoreline position from 1951/52 and 2010. The individual transects are coded with information such as length, angle and trend (erosion/accretion). The length of each individual transect was corrected in our spreadsheet to account for the lakeward position of the 2010 shoreline due to a lake level that was 2.25 feet lower than the conditions that existed in 1951/52. The corrected transect information was used to characterize the change in shoreline position at the individual transects and establish regional trends or reaches within the study limits.

RESULTS

The study area from Michigan City to Gary Indiana has been sub-divided into seven reaches based on the recorded long term shoreline change trends. The reach name, length, trend and average shoreline change rate is summarized in table 2 and visually in the figures attached at the end of this report. To note that the erosion transects are shown in red and the accretion transects are depicted in yellow.

TABLE 2: SHORELINE REACHES AND LONG-TERM TREND (1951/52 TO 2010)

Reach	Name	Approximate Length	Trend	1951/52 to 2010 Average Shoreline Change Rate
Michigan City				
A	Mount Baldy Erosion Zone	11,300 ft	Erosion	4.5 ft/yr
B	Beverly Shores to Dune Acres	42,600 ft	Dynamically Stable	n/a
C	Port of Indiana Industrial Complex Fillet Beach	7,700 ft	Accretion	7.6 ft/yr
Port of Indiana Industrial Complex				
D	Burns Waterway Small Boat Harbor–Fillet Beach	3,900	Accretion	2.1 ft/yr
E	Town of Ogden Dunes	3,900 ft	Erosion	2.7 ft/yr
Gary Indiana / U.S. Steel				
F	West Beach to Miller	15,100 ft	Dynamically Stable	n/a
G	Gary USX Steel Harbor–Fillet Beach	11,500 ft	Accretion	5.1 ft/yr

Notes:
ft = feet
ft/yr = feet per year
U.S. = United States

The shoreline transects for the study area are plotted in detail on a series of formatted map panels and attached to this report. Each map presents the 1951/52 photograph with the 1951/52 and 2010 shorelines and the 2010 photograph with the 1951/52 and 2010 shorelines overlaid. On these maps, the shoreline position was not corrected. However, the individual transect measurements were corrected for the shoreline change rates reported in table 2 above.

It is also worth noting that the 1971 shoreline is also included on the individual map tiles. The difference in the lake level from 1951/52 to 1971 was 0.25 ft and thus the actual positions can be compared without a correction. This photo series was selected for the analysis since it corresponded closely to the post-construction era for the Port of Indiana and Gary. A summary of the shoreline change analysis results is presented as follows.

Reach A: Downdrift of the Michigan City jetties and the steel sheet pile wall protecting the NIPSCO property, the Mount Baldy erosion zone extends approximately 2 miles. The long-term erosion rate for this reach is 4.5 ft/yr. Without the ongoing nourishment program, the erosion rate would be even higher.

Reach B: This reach extends from the Beverly Shores community to the western limits of the Dune Acres, a total distance of 8 miles. Between 1951/52 and present, once the transect measurements were corrected for lake level differences, the average rate of change was accretion of approximately 0.3 ft/yr (which is likely within the error limits of the analysis). The present waterline position is heavily influenced by the current period of low lake levels. Once high lake levels return, a considerable amount of this accreted beach will erode. Also, for many of the transects, the trend from 1951/52 and 1971 was actually erosion. Therefore, this portion of the study area has been classified as dynamically stable. In other words, both periods of erosion and accretion have occurred and will occur in the future. The product of these shoreline fluctuations is a net change of close to zero.

The dynamic nature of this shoreline is further highlighted by the 1951/52 to 2010 shoreline comparison for the Beverly Shores area. Although the beach has migrated lakeward from 1951/52 to 2010, some of cottages that were located lakeward of the road are now gone. It is possible they were lost or damaged during the high lake period between early 1970 and late 1990. The visible waterline in the 1971 photo series confirms that parts of the shoreline eroded during this period of high lake levels.

Reach C: The updrift fillet beach at the Port of Indiana Industrial Complex is 1.5 miles in length and has been rapidly accreting since the port was constructed. The average accretion rate is 7.6 ft/yr. Without the Port of Indiana Industrial Complex, this sediment would be spread along the beaches of Ogden Dunes to Marquette Park.

Reach D: Since the construction of the jetties at the mouth of the Burns Waterway Small Boat Harbor, the relatively straight 1971 shoreline is re-aligned against the jetties. The average accretion rate from 1951/52 to 2010 is 2.1 ft/yr) for a distance of approximately 0.75 miles. However, based on the position of the 1971 shoreline, it appears the sand in this sub-cell has just migrated into the present fillet beach (not a net gain to the sub-cell).

Reach E: The beach fronting the Town of Ogden Dunes community has a long-term erosion rate of 2.7 ft/yr, which is attributed to the sediment starved conditions created by the Port of Indiana Industrial Complex.

Reach F: Between the Port of Indiana Industrial Complex and Gary USX Steel Harbor, 2.8 miles of shoreline is classified as dynamically stable. Although the average transect change rate was accretion of 0.65 ft/yr, this rate of change is considered to be within the error of the analysis and is also highly influenced by the present low water conditions. The position of the 1971 shoreline was very similar to the 1951/52 conditions. The present wide beach conditions could change significantly during average or high lake levels.

Reach G: The fillet beach adjacent to the Gary USX Steel Harbor-east breakwater is 2.2 miles in length and features an average accretion rate of 5.1 ft/yr. A significant volume of sediment has accumulated in this region and this process will continue, especially if dredging around NIPSCO intake and mechanical bypassing continue. At some point in the future, sediment will migrate along the outer limit of the Gary USX Steel Harbor and some will accumulate in the navigation channel.

USACE INDIANA SHORELINE MONITORING REPORT (2008)

The USACE has been nourishing the shoreline downdrift of Michigan City since 1974. In 2008 a comprehensive monitoring report was prepared to review the shoreline evolution between Michigan City and the Port of Indiana using aerial photographs and beach profile surveys. The following bullet points highlight key findings relevant to the present investigation for Indiana Dunes National Lakeshore:

- Between 1974 and 2004, nourishment was placed on the beach immediate east of Mount Baldy on 11 out of 30 years. A total of 925,000 cubic yards was placed from upland sources and sediment bypassed at Michigan City, for an annual average of approximately 30,800 cubic yards.
- Baird's (2004) sediment budget study determined there was a 105,000 cubic yard deficit at Mount Baldy due to the sand trapped at Michigan City. Therefore, despite the substantial effort to nourish the beaches downdrift of the harbor, erosion will continue until this deficit is substantially reduced.
- Since the focus of the investigation was monitoring downdrift shoreline evolution following the beach nourishment, aerial photographs were analyzed from 1979, 2000 and 2005. A 2 ft contour was derived from the photographs by digitizing the shoreline and adjusting the position landward or lakeward using a fixed beach slope. A fourth 2 ft contour was derived from a 1997 SHOALS survey of the study area.
- Shoreline change measurements were made of 400 ft intervals along a baseline from 1979 to 2005, then annualized as ft/yr. Qualitative descriptors were also generated for the measurements at 400 ft intervals. Figure 18 from the USACE report is reproduced in this report.
- The shoreline change analysis generally identified similar trends to the results summarized in this report, with significant erosion fronting the Mount

Baldy dunes even in light of the beach nourishment and a large accretion zone to the east of the Port of Indiana/NIPSCO plant. For the central portion of the shoreline (Beverly Shores and State Park), the USACE report identified accretion rates ranging from "very slow" to "moderate" to a few isolated cases of "rapid". The "rapid" classification appears to be attributed to sand waves moving along the coastline. The Baird analysis in this report for the central region concluded the shoreline was dynamically stable but it should be noted the duration of our analysis was much longer (1952/52 to 2010). From 1951/52 to 1971 the shoreline actually eroded in some locations, which was part of the rationale for classifying this region as dynamically stable. It should also be noted when positional errors due to photo registration and digitizing the shorelines are considered, small rates of change actually fall within the error limits of the analysis. Refer to Zuzek et al. (2003).

- Nine beach profiles offshore of Mount Baldy were analyzed from 1997 to 2005. Based on a 3 dimensional surface comparison of the raw point data, the net lakebed change was a small gain of 0.1 ft (averaged across the entire area). Refer to the figure reproduced in this report. It should be noted that the change was not uniform, with significant accretion at the shoreline (0 to +6 ft). This accretion was likely attributed to both the beach nourishment program and the significant drop in lake levels from 1997 to 2005. Offshore of the beach, there are significant areas were lakebed erosion ranging from 1 to 4 feet were documented. As the lakebed in this region is presumed to be exposed glacial sediment (lacustrine clay), this erosion represents the permanent removal and lowering of the lake bottom. This finding is an important design consideration for developing long-term shoreline stabilization options for the park in the future.

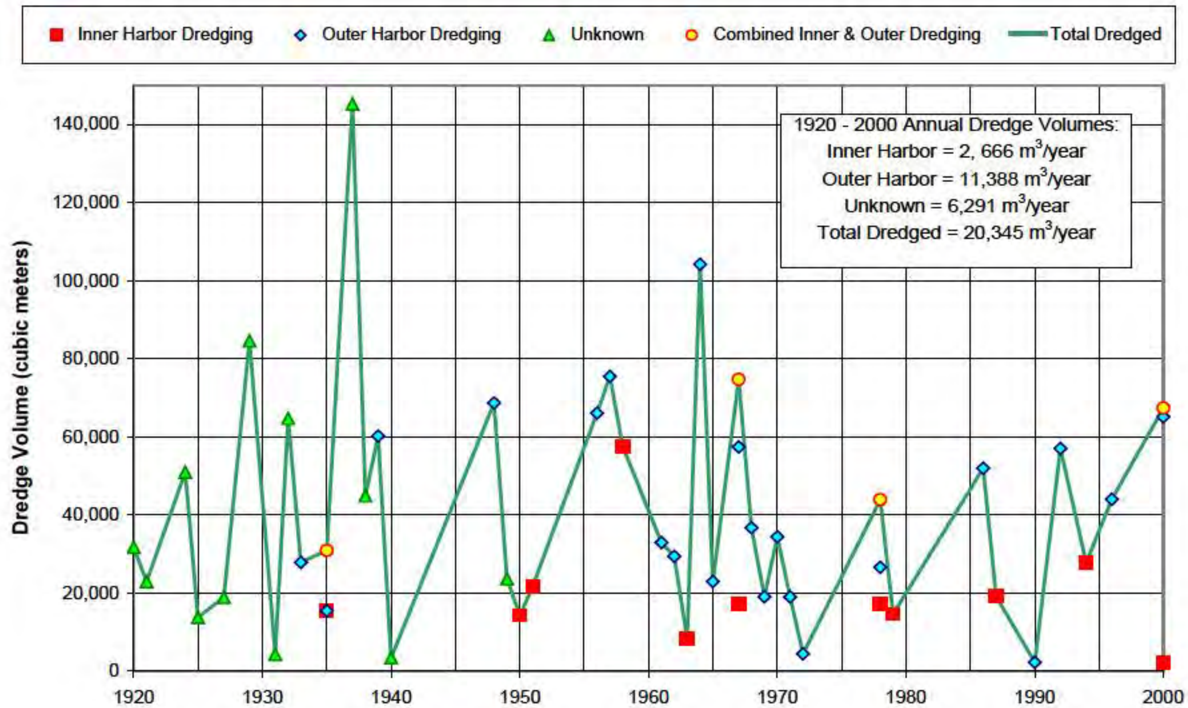
DREDGING AND BEACH NOURISHMENT SUMMARY

Dredging and beach nourishment data in the project area has been compiled from various sources. This data, together with the shoreline evolution analysis, will provide useful information in support of the shoreline restoration alternatives. The dredging and beach nourishment records for Michigan City were assembled by the USACE-Chicago District from 1920 to 2000. Data for Burns Harbor Waterway, Burns Small Boat Harbor and NIPSCO/Bailly Intake has been summarized from USACE from 1980 to 2009. The Mount Baldy beach nourishment data has been assembled from both NPS and USACE data.

Michigan City

The historical records provided the year and volume of sediment removed from the lake bed, but the location of the dredging is not specified. Consequently, the location of the dredging is categorized as: inner harbor, outer harbor, combined inner and outer harbor or unknown. The results of this analysis are presented graphically for the period of 1920 to 2000 in figure 6. The individual colored symbols indicate the location of the dredging, while the green line is the cumulative yearly total, regardless of location.

FIGURE 6: MICHIGAN CITY DREDGING SUMMARY



Burns Waterway, Small Boat Harbor and NIPSCO/Bailly

The historical records provided the for Burns Waterway Harbor between 1986 and 2009 show that a total of 537,000 cubic yards have been dredged, and placed as open-water disposal offshore of the Harbor.

Dredging records between 1985 and 2009 for the Burns Small Boat Harbor show that 282,000 cubic yards of materials have been removed and placed on the beach immediately west of the harbor breakwater (NPS Portage Lakefront), and in the near-shore area of Ogden Dunes.

The NIPSCO/Bailly water intake location has been dredged to -21 feet water depth at LWD since 1980 by NIPSCO and, starting in 2006, by USACE. The maintenance program has been irregular, making planning predictions of future dredging needs difficult.

A total of 2,212,000 cubic yards of sand has been removed and primarily placed in the near-shore area in front of Ogden Dunes (1,487,500 cubic yards) while Beverly Shores received a total of 311,500 cubic yards. The remaining quantity had an unspecified open-water placement location.

One noteworthy finding is that the Ogden Dunes beach nourishment started to occur in 1986, allowing placement of material 1,500 feet offshore, and 1,500 feet west of the Burns Waterway Small Boat Harbor inner breakwater. The dredged material placement involves open water disposal in a water depth between 12 feet (considered safe draft for opening split-hull barges bottom hull) and 18 feet (considered safe water depth in order not to allow the placed sand to migrate offshore). The most current permit (revised in 1995) allows placement within 1,500 feet of the shoreline.

Based on consecutive 2006, 2007, 2008, and 2009 dredging quantities, an average annual quantity of 118,000 cubic yards has been removed from the NIPSCO intake and placed at Ogden Dunes. To note that for 7 consecutive years (between 1999 and 2006) no dredging occurred. On a long-term (1986 to 2009) average basis, approximately 74,000 cubic yards have been placed at Ogden Dunes.

The Beverly Shores area was nourished only between 1986 and 1999, with an average quantity of 52,000 cubic yards per dredging event. No other nourishment records were found. Table 3 shows a summary of the Burns Waterway, Small Boat Harbor, and NIPSCO/Bailly quantities dredged.

TABLE 3: DREDGING SUMMARY FOR BURNS WATERWAY SMALL BOAT HARBOR (1980 TO 2009)

Project	Year	Qty. (cyds)
Burns Waterway Harbor	2009	49,000
	2008	55,000
	2007	100,0000
	1996	266,000
	1986	67,000
Burns Small Boat Harbor	2009	80,000
	2000	143,000
	1985	59,000
NIPSCO Intake (USACE Dredging)	2009	110,000
	2008	105,000
	2007	228,000
	2006	30,000
NIPSCO Intake (USACE Dredging)	1999	165,000
	1997	146,000
	1995	118,000
	1992	209,000
	1989	288,000
	1986	320,000
	1982	218,000
	1980	275,000
Total		3,3031,000

Mount Baldy

The beaches fronting Mount Baldy have been nourished since 1974. A total of 792,884 cubic yards have been trucked to the site from upland sources and placed on the beach. In addition, 371,373 cubic yards of sediment dredged hydraulically from the Michigan City Harbor has been placed on the beach. When annualized, approximately 31,465 cubic yards of sand has been placed since 1974 as a long-term average quantity. To note this is a lot less than the calculated 105,000 cubic yards deficit needed due to the sand trapped at Michigan City.

Therefore, despite the efforts to stabilize the shore, the beach and dune continue to erode at Mount Baldy. A summary of the Mount Baldy beach nourishment is presented in table 4.

TABLE 4: BEACH NOURISHMENT FOR MOUNT BALDY (1974 TO 2008)

Project	Year	Upland (Trucking) Qty. (cyds)	Michigan City Harbor (Hydraulic Dredging) Qty. (cyds)
Mount Baldy Beach Nourishment*	2010	56250	
	2008	17,273	30,159
	2007	17,273	
	2005	9500	13,962
	2004	17,500	
	2003	52,298	51,119
	2001	42,750	
	2000		85,251
	1999	36,000	
	1998	107,000	
	1997	73,000	
	1996	57,000	48,201
	1992		74,642
	1987		68,039
	1981	80,000	
	1974	227,000	
Total		792,844	371,373

Notes:
cyds = cubic yards
qty = quantity

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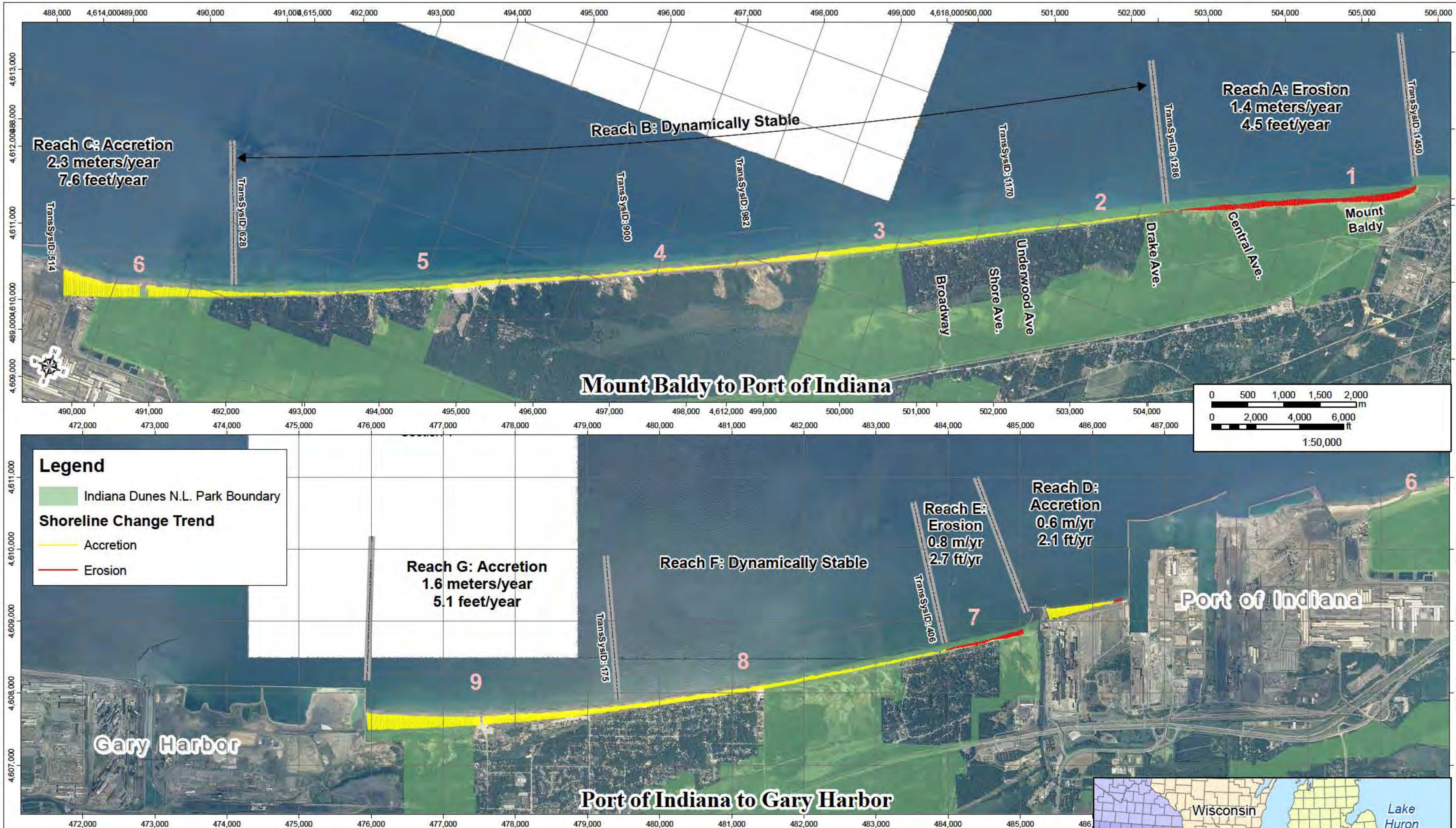
Zuzek, P.J., R.B. Nairn, and S.J. Thieme
2003 Spatial and Temporal Considerations for Calculating Shoreline Change Rates in the Great Lakes Basin. Journal of Coastal Research, Special Issue No. 38.



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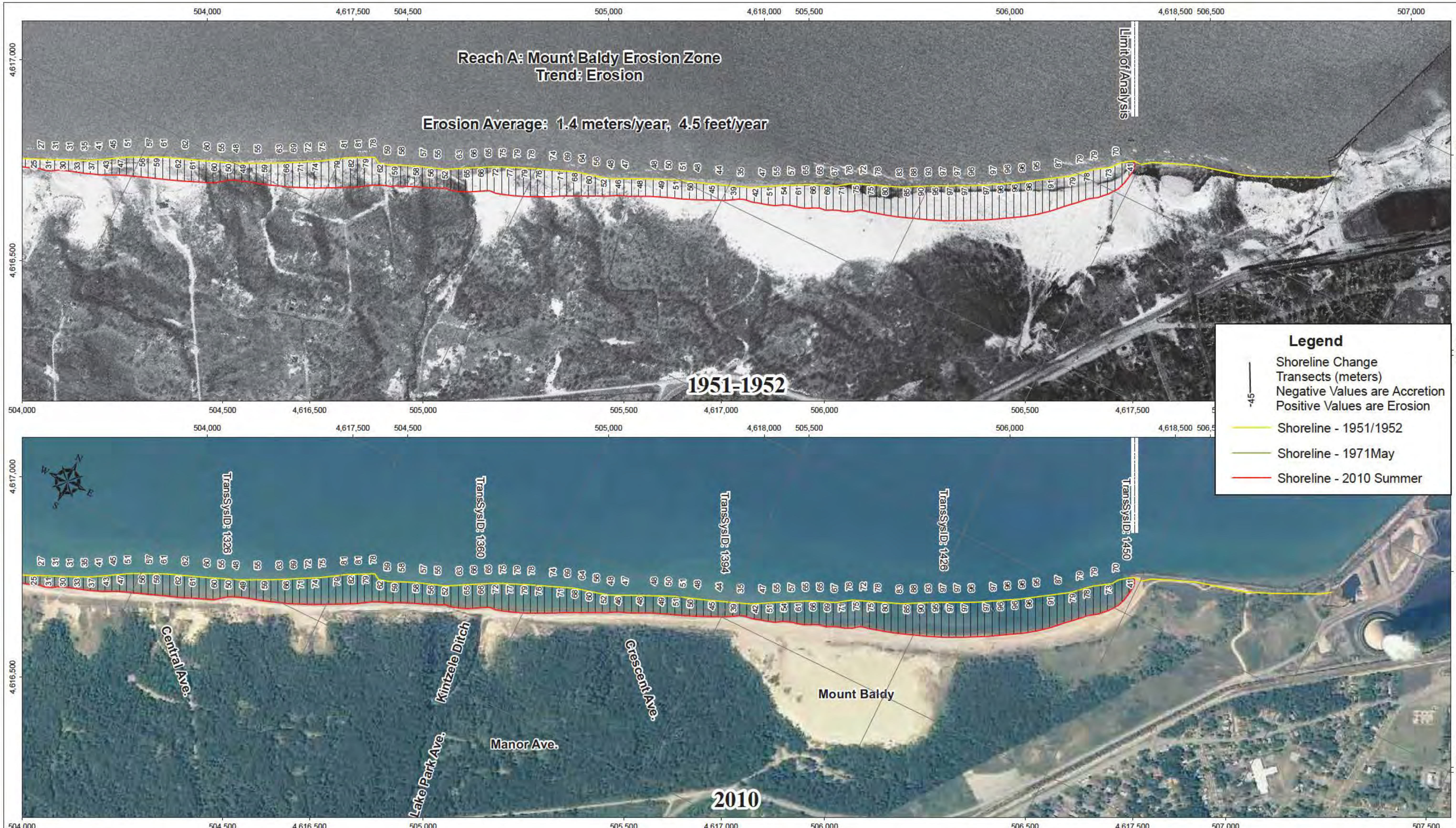
Summary of Regional Shoreline Change Analysis (1951/52 to 2010)

Mount Baldy to Gary Harbor



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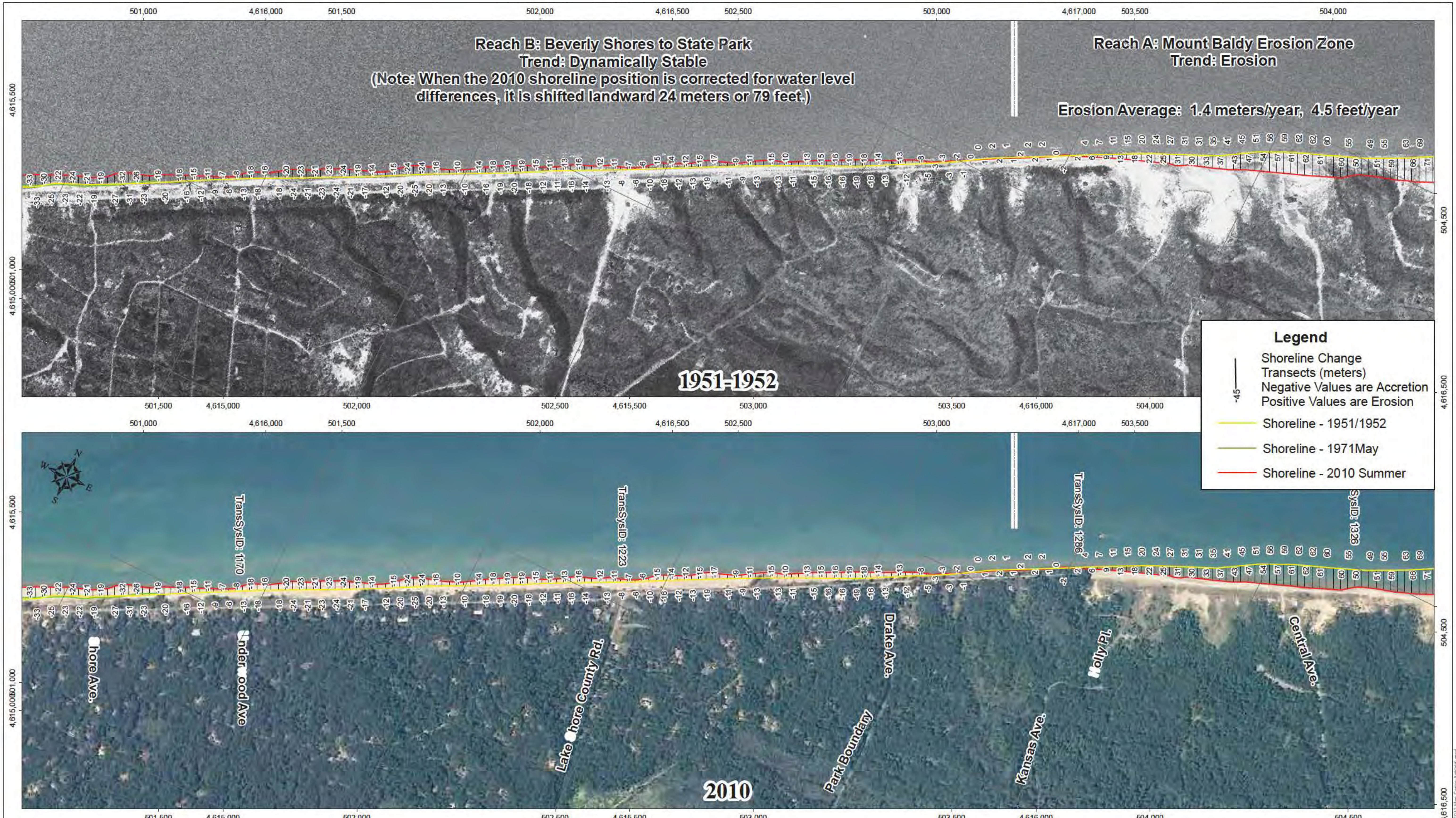
Top Airphotos: Dec 1951 and March 1952, USGS
Bottom Airphoto: Summer 2010 mosaic, USDA NAIP
Grid Spacing: 500 meters
Spatial Reference: UTM zone 16

1951/52 to 2010 Shoreline Comparison (transects in meters)

Note: Shoreline position in 1951/52 and 2010 not adjusted for lake level differences on these maps. However, individual transect values were adjusted for lake levels for the rates reported on these maps.



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Bottom Airphoto: Summer 2010 mosaic, USDA NAIP
Grid Spacing: 500 meters
Spatial Reference: UTM zone 16

1951/52 to 2010 Shoreline Comparison (transects in meters)

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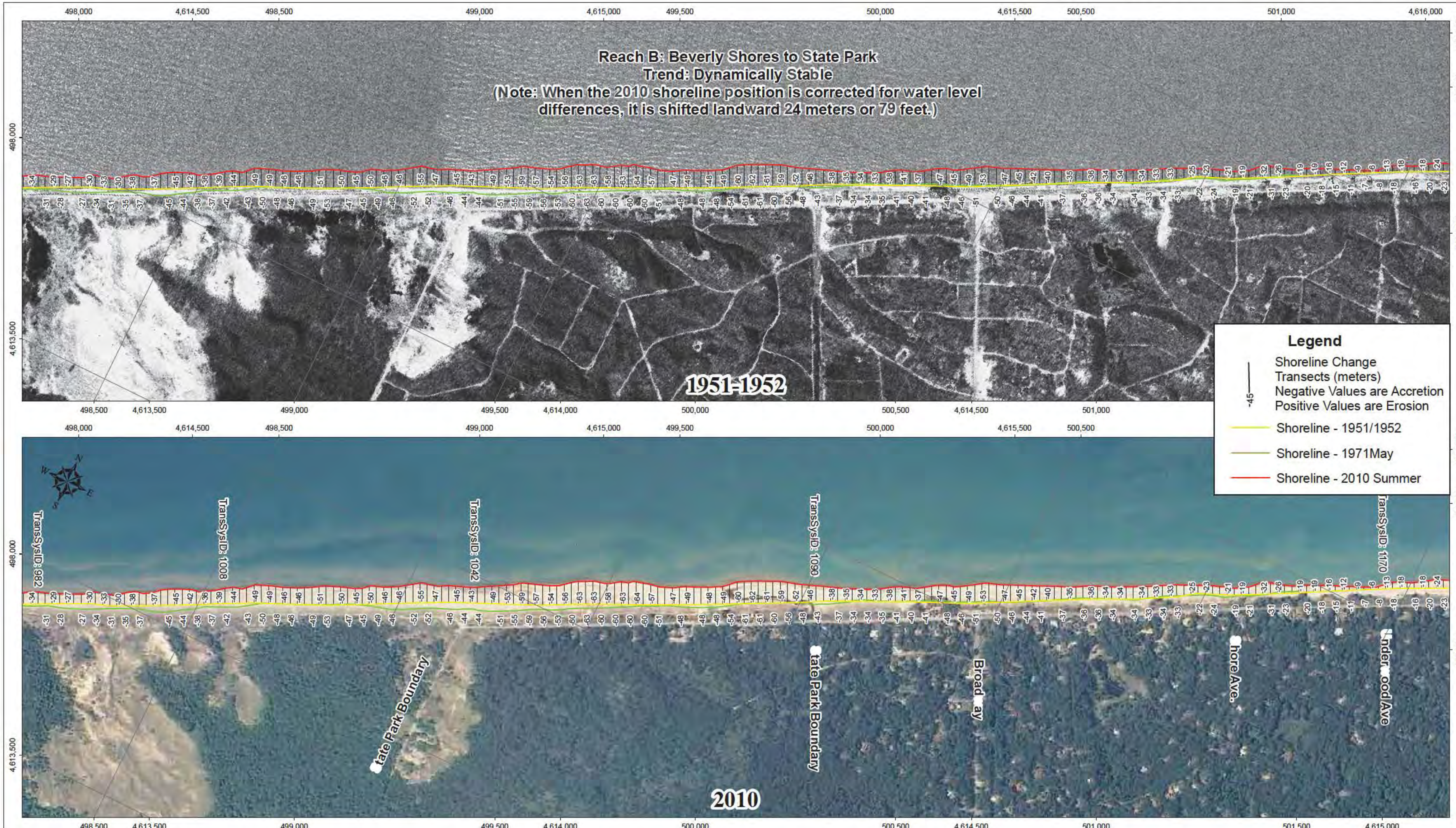

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Top Airphotos: Dec 1951 and March 1952, USGS
Bottom Airphoto: Summer 2010 mosaic, USDA NAIP
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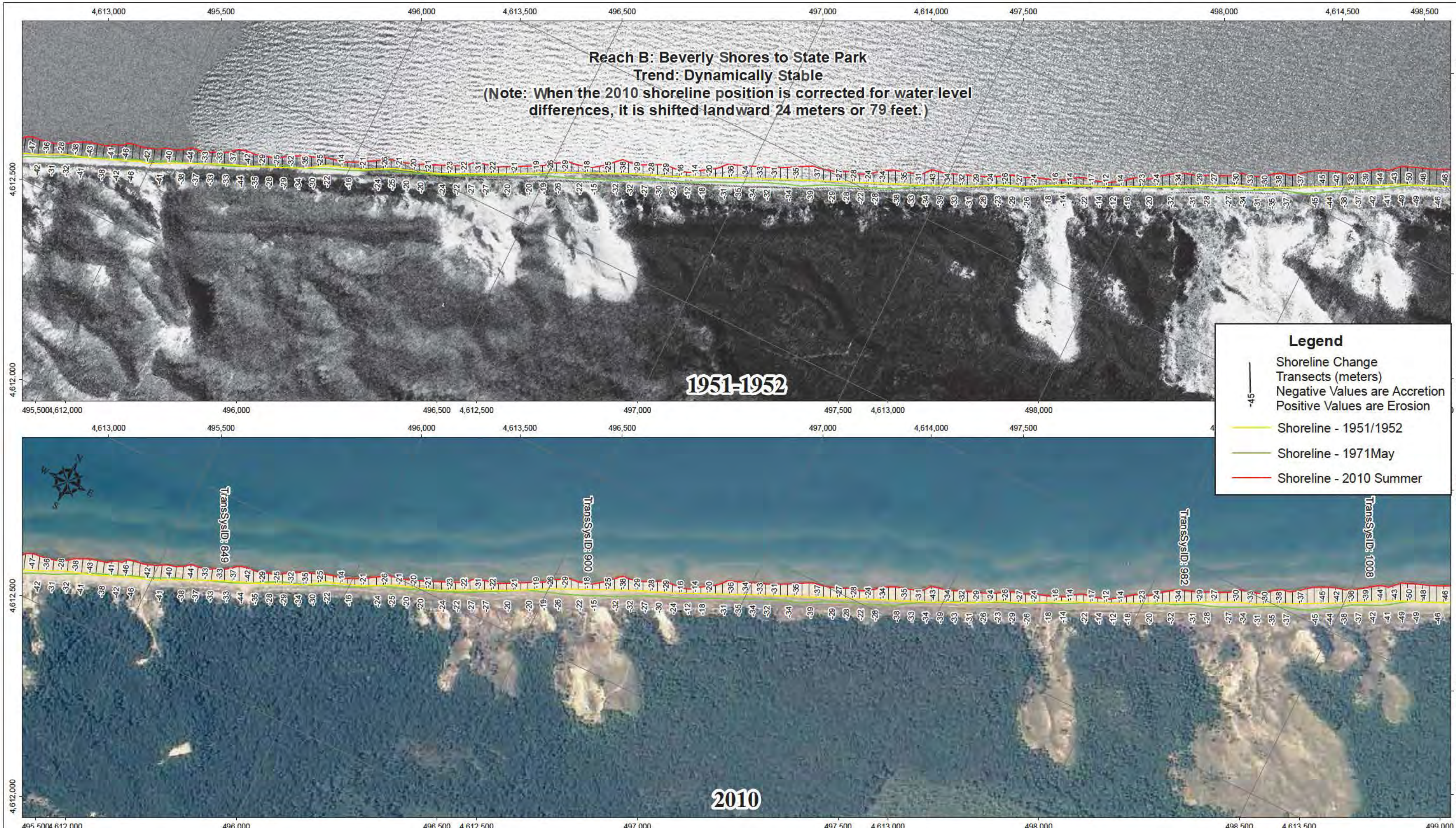

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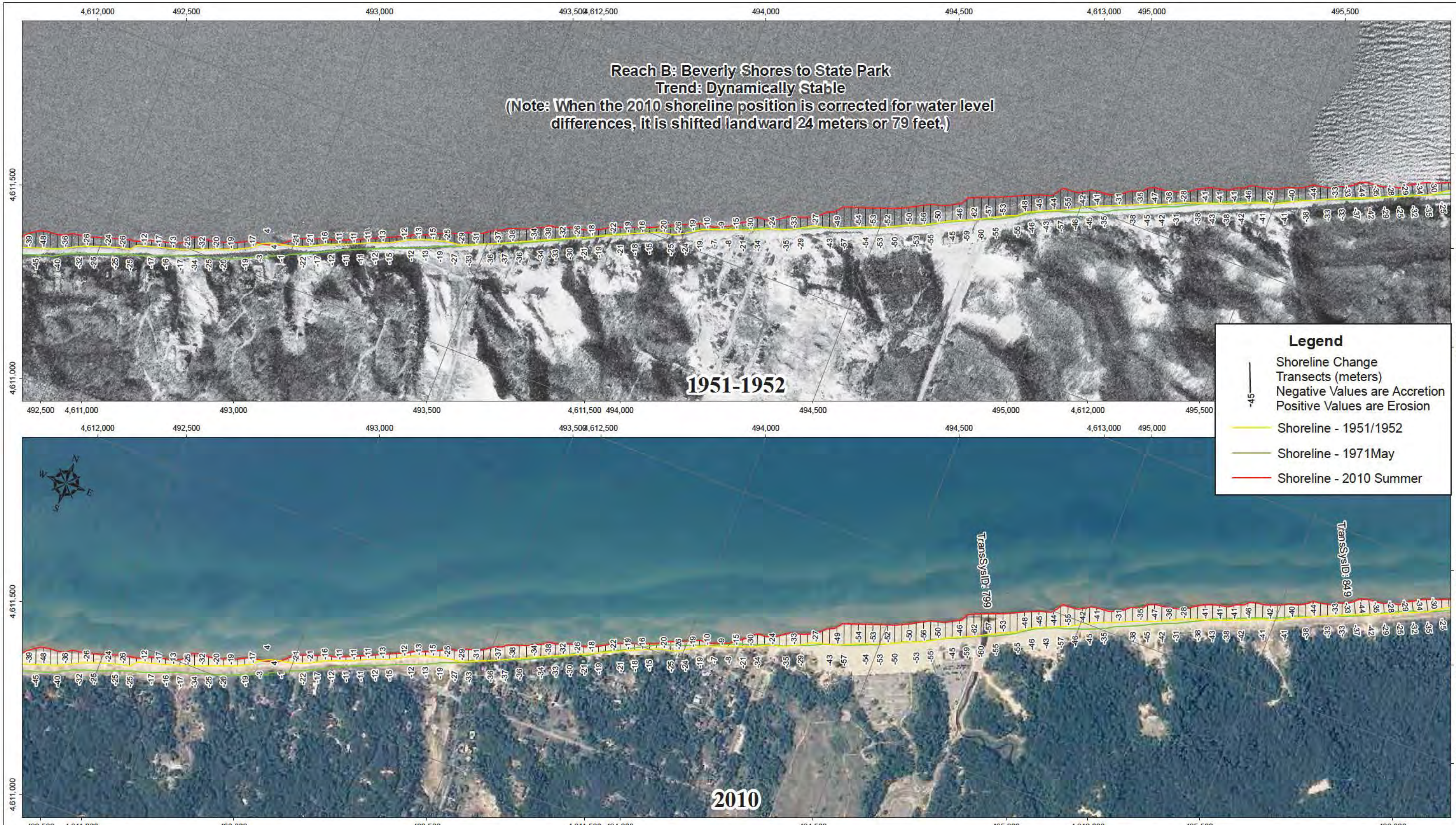

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Top Airphotos: Dec 1951 and March 1952, USGS
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1951/52 to 2010 Shoreline Comparison (transects in meters)

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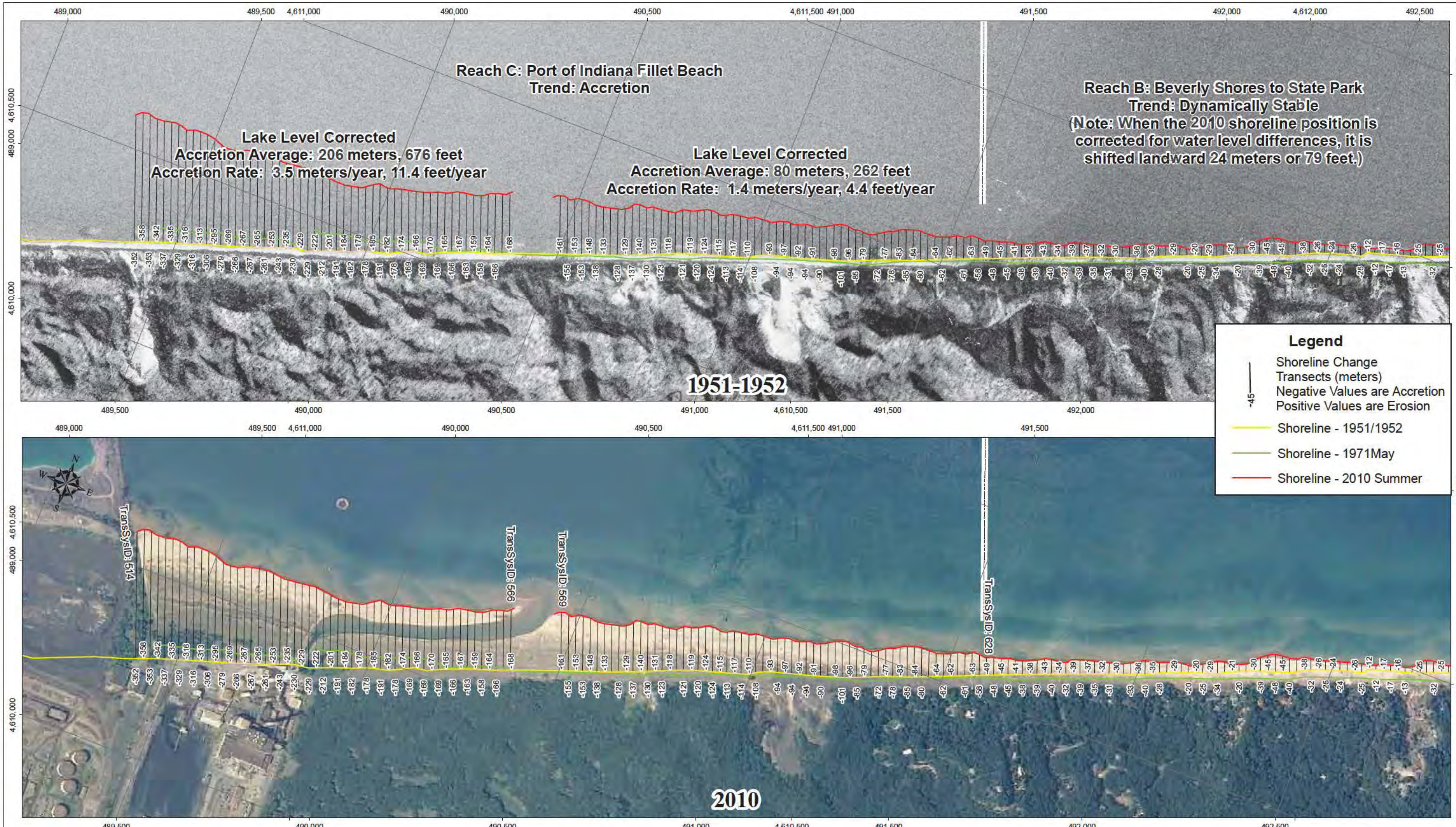

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Bottom Airphoto: Summer 2010 mosaic, USDA NAIP
Grid Spacing: 500 meters
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1951/52 to 2010 Shoreline Comparison (transects in meters)

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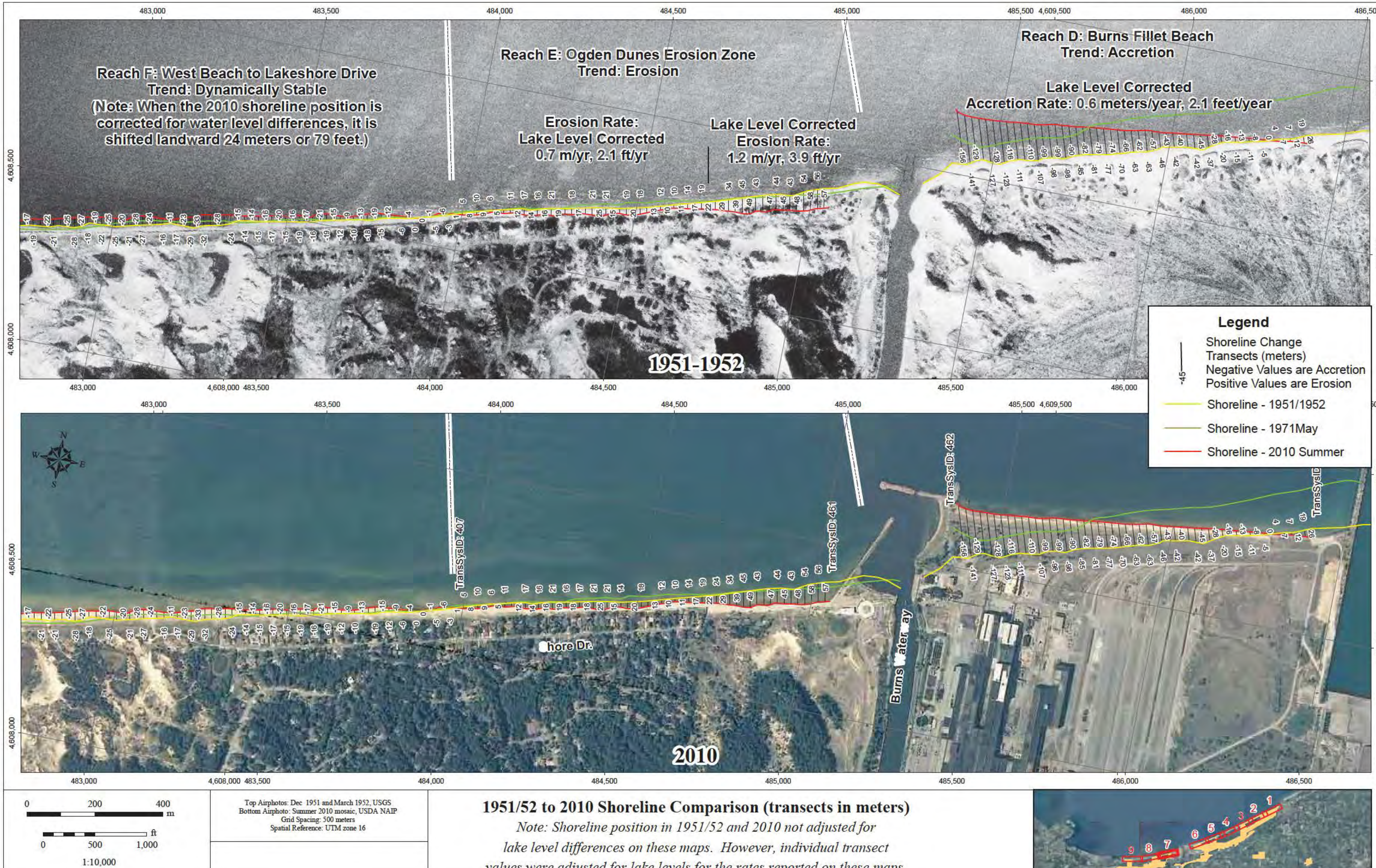

Top Airphotos: Dec 1951 and March 1952, USGS
Bottom Airphoto: Summer 2010 mosaic, USDA NAIP
Grid Spacing: 500 meters
Spatial Reference: UTM zone 16

1951/52 to 2010 Shoreline Comparison (transects in meters)

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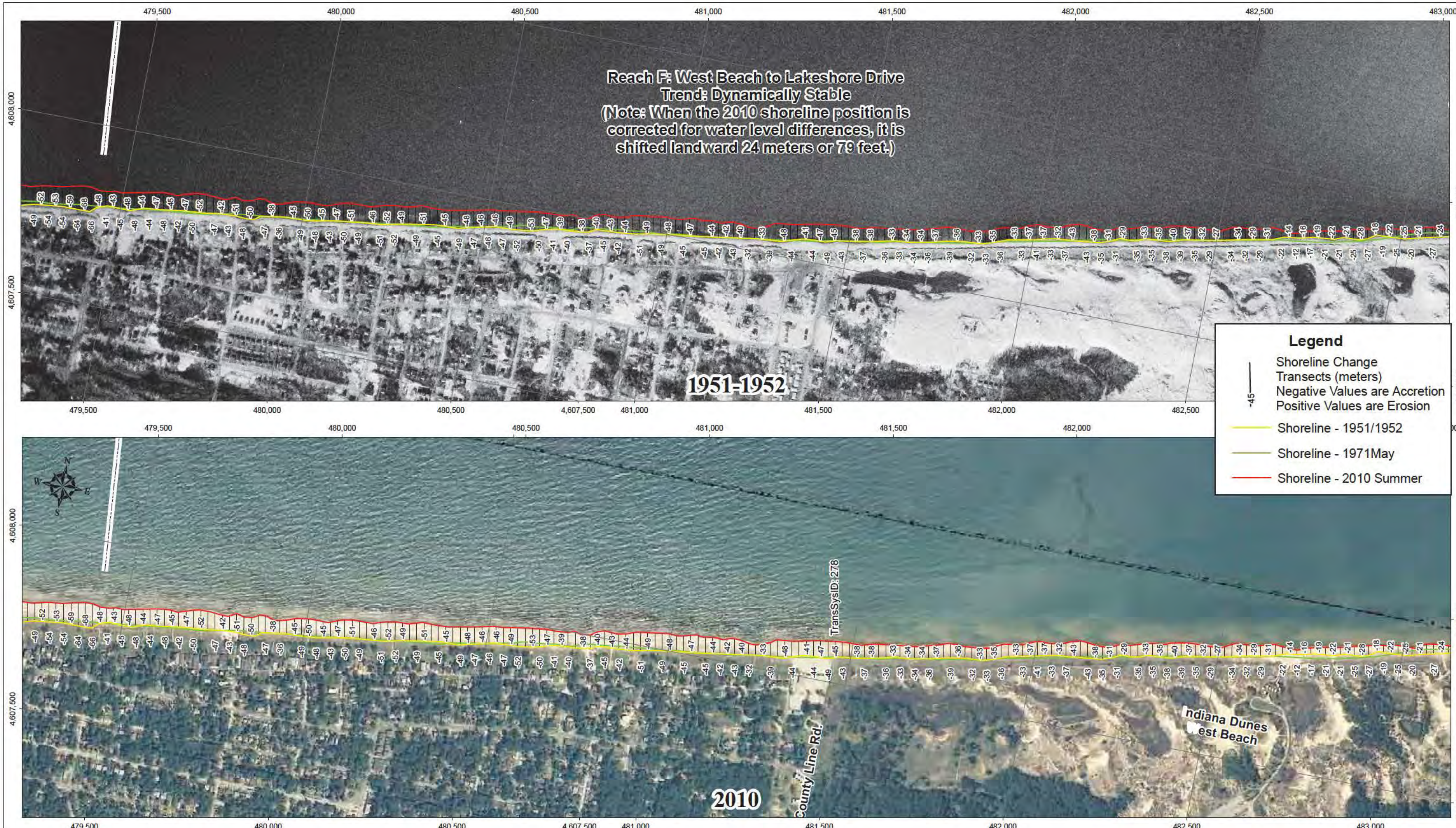

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Top Airphotos: Dec 1951 and March 1952, USGS
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Top Airphotos: Dec 1951 and March 1952, USGS
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Grid Spacing: 500 meters
Spatial Reference: UTM zone 16

1951/52 to 2010 Shoreline Comparison (transects in meters)

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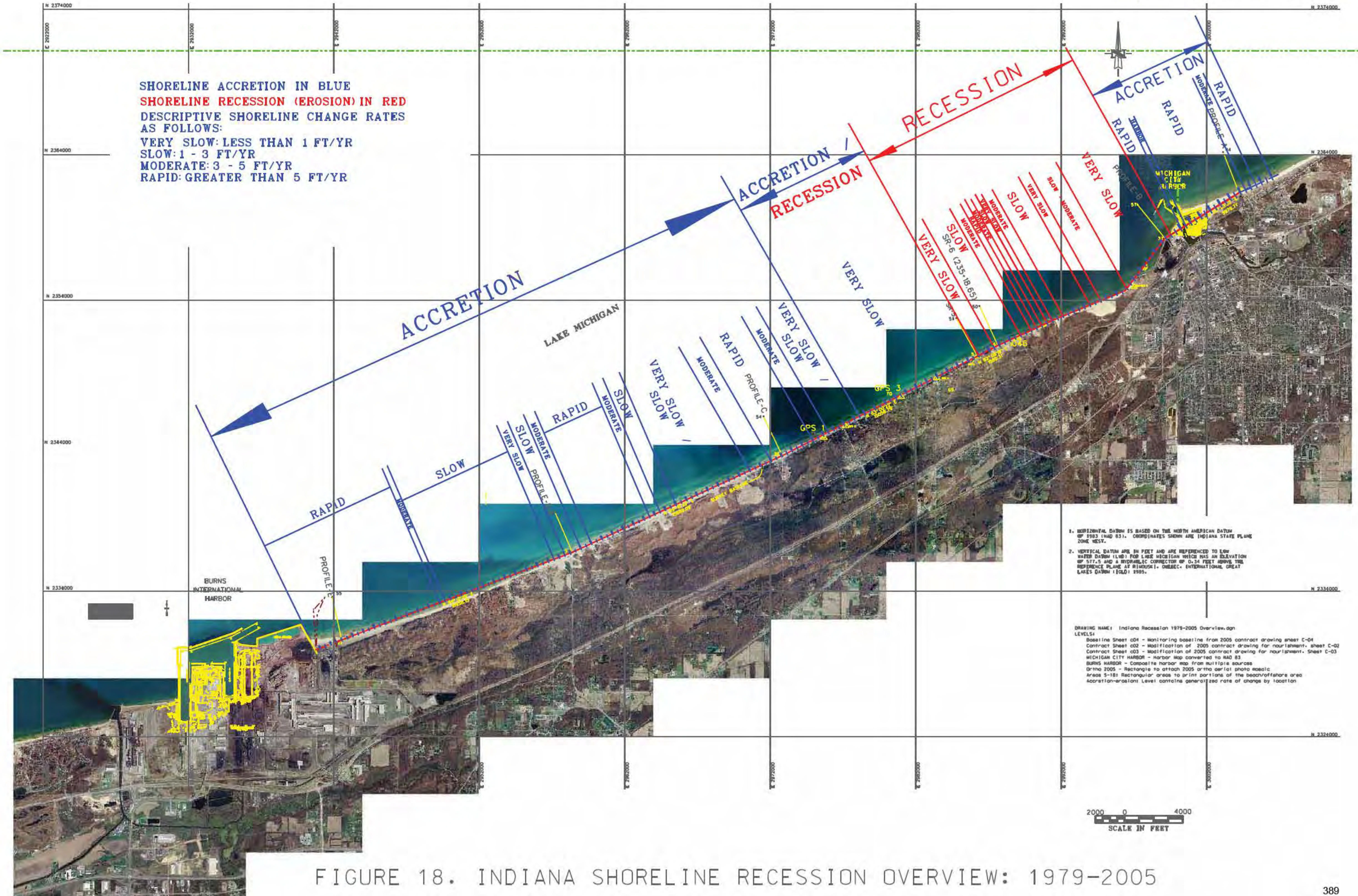
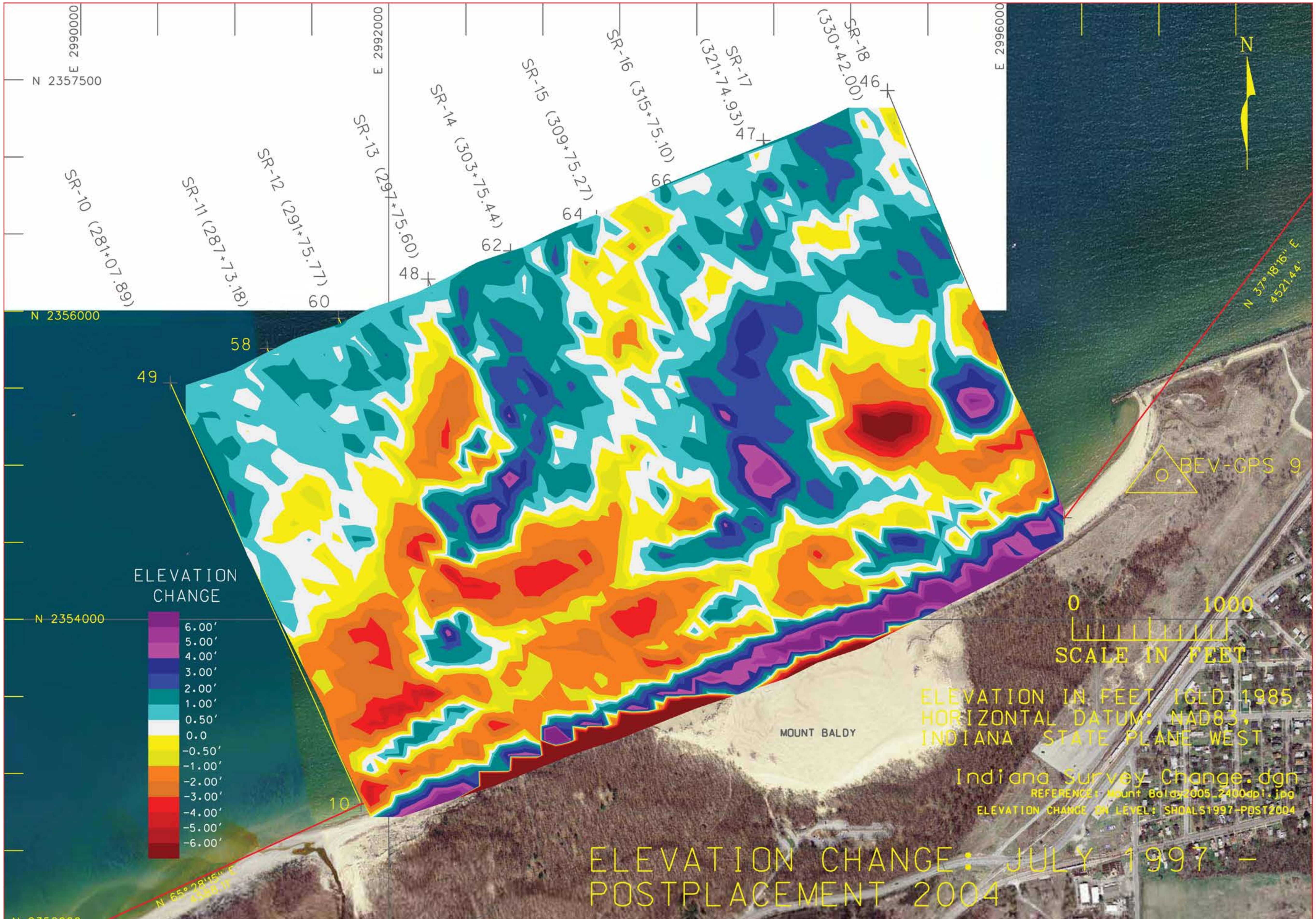


FIGURE 18. INDIANA SHORELINE RECESSION OVERVIEW: 1979-2005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SR-13 (297+75.60)
SR-14 (303+75.44)
SR-15 (309+75.27)
SR-16 (315+75.10)
SR-17 (321+74.93)
SR-18 (330+42.00)
46
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INDIANA STATE PLANE WEST
Indiana Survey Change.dgn
REFERENCE: Mount Baldy2005_2400dpi.jpg
ELEVATION CHANGE ON LEVEL: SHOALS1997-POST2004
MOUNT BALDY
ELEVATION CHANGE: JULY 1997 -
POSTPLACEMENT 2004

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